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District Cooling in Lima, Peru

Identification of potentials and barriers for developing district cooling in the San Isidro financial district

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Master Thesis

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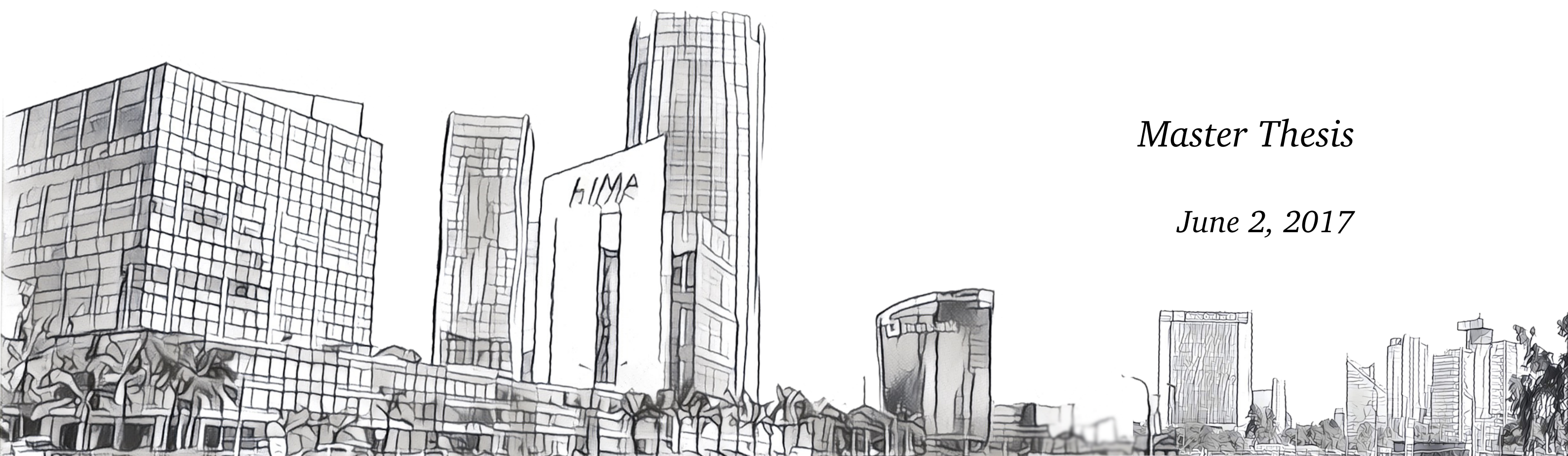

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Master Thesis:

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Abstract

The district of San Isidro in Lima, Peru, is the countries major business hub and as such, a high density of high value buildings are located there. Cooling needs in these type of buildings are significant, and represent a large portion of their total electricity consumption. Currently, this cooling demand is met using conventional cooling technologies, such as centralized air conditioning systems. District cooling may provide a more efficient and less polluting alternative to that of conventional technologies. This project explores the potential of implementing a district cooling system in the financial zones of San Isidro district, by assessing the techno-economic cost benefit, and the institutional conditions present in Peru. The results of the analyses show that a district cooling system might be feasible, but many institutional and practical barriers currently exist that may hinder such a development.

Preface

This thesis report has been elaborated in fulfillment of the Sustainable Energy Planning and Management master program at Aalborg University. The thesis has been written in the spring term, spanning from February 1, 2017 to June 2, 2017. However, the initial catalyst leading up into developing a research topic about district cooling can be traced back to much earlier. Before this research process began, Miguel's years of exposure to what he refers to as Lima's "insufferable summer" lead him to question why space cooling was not more widespread in the city. In contrast, Daniel's life in the lands of ice and always-winter lead him to wonder what life would be like in warmer places. This curiosity naturally resulted in the work collaboration embodied by this thesis report. The final catalyst for this idea to come into shape, of course, came much later; after taking inspiration from a keynote presentation about the potential and worldwide developments of district energy, held at the *2nd International Conference on Smart Energy Systems and 4th Generation District Heating* in Aalborg, Denmark.

Before the reader moves onto the main body of the report, a few things need to be considered for better digesting the contents here presented. Sections, tables and figures are numbered chronologically, according to their chapter numbers. Values displayed in tables and graphs were rounded depending on their magnitude. Since the calculations were performed with the original values, slight discrepancies may arise when comparing the results displayed in this report. In addition, all monetary values are presented in U.S. Dollars (USD) as it stood on January 1, 2017 with regards to inflation and exchange rate. Cited sources presenting values in other currencies – namely Peruvian Soles (PEN), Euros (EUR), and Danish Kroner (DKK) – were converted accordingly using the following exchange rates: 1 USD = 3.41448 PEN = 0.92076 EUR = 7.0667 DKK.

To close, we would like to give credit to a number of people, without whom this thesis project would not be where it stands. Thanks are due to *Steffen Nielsen*, from the Energy Planning Group at Aalborg University's Department of Development and Planning, for his suggestions and supervision throughout the process of developing this thesis report. Additionally, we would also like to extend our gratitude to the following data contributors and interviewees for their valuable inputs and guidance: *Lily Riahi, Jaime Cabrera, Philip Reiser, Daniella Rough, Roberto Prieto, Pamela Peña, Veronica Yañez, Karin Cappillo, Anali Ochoa, Francesca Mayer, Romanas Savickas, Zhoulun Chen, and Mikkel Willum.*

Finally, we would like to thank our respective families, friends, and table neighbors for their constant support.

We wish you a pleasant reading!

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Nomenclature

BAU	Business As Usual
$CAPEX$	Capital Expenditure
CDD	Cooling Degree-Days
$CO2$	Carbon Dioxide
COP	Coefficient of Performance
DC	District Cooling
EU	European Union
GHG	Greenhouse Gases
GIS	Geographic Information System
$LCOC$	Levelized Cost of Cooling
MCZ	Metropolitan Commercial Zone
$MINAM$	Ministry of Environment
$MINEM$	Ministry of Energy and Mines
MSI	Municipality of San Isidro

$MVCS$	Ministry of Housing, Construction and Sanitation
$NAMA$	Nationally Appropriate Mitigation Action
NPC	Net Present Cost
NPV	Net Present Value
$O\&M$	Operation and Maintenance
$OPEX$	Operational Expenditure
$OSINERGMIN$	Supervisory Agency for Energy and Mining Investment
$PeruGBC$	Peru Green Building Council
SRZ	Special Regulatory Zone
TES	Thermal Energy Storage
$UNEP$	United Nations Environmental Program

1 Introduction

> *District cooling is becoming increasingly relevant as cooling demand surges worldwide.*
>
> — **Lily Riahi**
> (UNEP, 2015)

Over the past few decades, Peru has undergone exemplary economic growth above the regional Latin American average, as well as major public policy reforms. Much of this growth has been centered in Lima, Peru's capital and most populated city, which has acted as a focal point for businesses and constructions, among other sectors (IMF, 2015; World Bank, 2015). In turn, the financial district of San Isidro, in Lima, has been one cluster location where many construction developments have taken place; ranging from corporate offices, company headquarters, hotels, and commercial enterprises, as well as residences (Avilez et al., 2011). The construction and building developments sprawled throughout the district — and more generally throughout the whole country — have done so until recent years without regulations that specifically address sustainability issues like energy efficiency. This specific issue is of particular importance due to the widespread use of inefficient systems and appliances (MVCS, 2015b), with conventional air conditioning systems constituting the highest share of the electricity consumption (MINEM, 2008) in the commercial, business and public buildings. Consequently, several government and private entities are leading the charge to adopt new measures with sustainable approaches towards construction and city planning that include energy efficiency as a major key component, among others (MVCS, 2015b).

Under this context, the aim of this thesis report is to explore the potential and the barriers for implementing district cooling connected to existing buildings as a solution to contribute to Peru's energy efficiency efforts parting from the case of Lima's financial district, San Isidro.

1.1 The Commercial and Public Sectors in the Peruvian Energy Context

Peru's energy mix is partially reliant on fossil fuels. As of 2015, the total energy production derived mostly from hydro power and natural gas. About 47% of the energy produced come from natural gas and oil sources, and 0.5% from coal. Renewable energy sources represent the other half of the mix, with hydro power accounting for approximately 48% in the mix, while other renewable energy sources like solar, wind and biomass represented the rest of the shares of total energy production (OSINERGMIN, 2016a).

The total energy consumption in Peru as of 2015 was 220.10 TWh (MINEM, 2016). Figure 1.1 shows the total energy use in Peru divided by sectors. As can be seen, the transport sector was the single largest consumer of energy using 91.93 TWh (42%), followed by the industrial and mining; and residential, public and commercial sectors, at 59.94 TWh (27.2%) and 58.40 TWh (26.5%) respectively. Agriculture and fishing used 5.22 TWh (2.4%) and other sectors used 4.64 TWh (2.1%) of energy (MINEM, 2016).

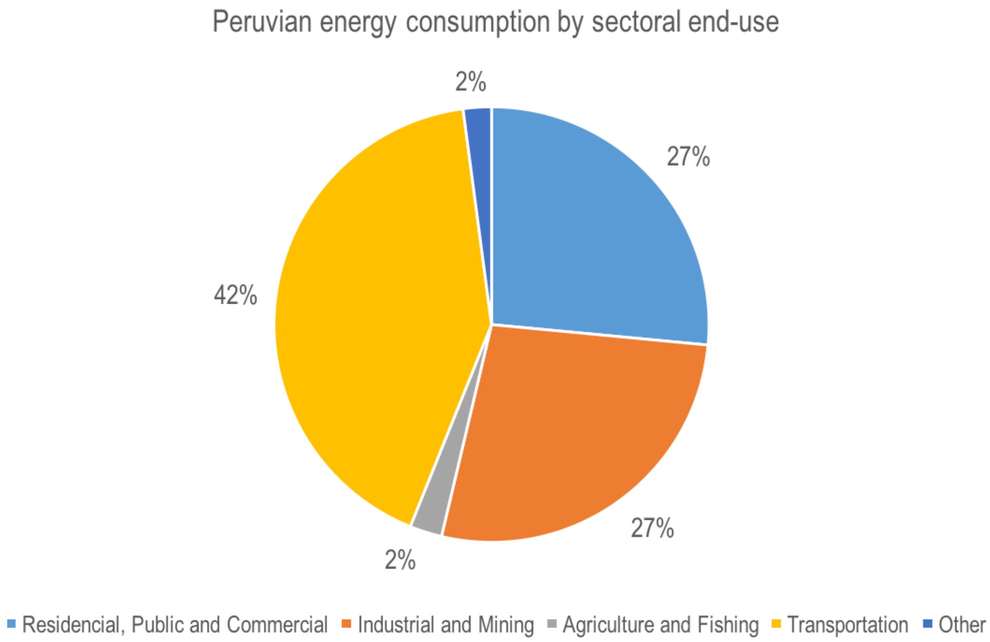

Fig. 1.1.: Peruvian energy consumption in 2015 by sectoral end-use. Source: MINEM (2016)).

The allocation of energy sources in the aforementioned sectors is not homogeneous. Consumption in the residential, public and commercial sectors is heavily reliant on electricity, which covers about 32% of the total consumption (MINEM, 2016). The electricity produced has, in turn, a large share of hydropower (50.7%) and smaller shares of fossil fuels (47.5%), wind power (1.3%), photovoltaics (0.5%) as primary energy sources (OSINERGMIN, 2015a). The residential, public and commercial sectors consume approximately 42% of the electricity generated from these sources (MINEM, 2016).

The subsequent use of electricity in the commercial and public sectors serve mostly to power electric appliances and other technical systems. Among the latter, as seen in Figure 1.2, conventional air conditioning systems amount to the highest electricity consumption share (35%) followed by lightning systems (33%), elevators (9%), refrigeration (6%), water pumps (6%), and other appliances (11%) (MINEM, 2008). According to a study commissioned by the Ministry of Energy and Mines MINEM (2008), inadequate use and user habits, as well as technology choices, could impact electricity usage of these items. Furthermore, MINEM identifies total electricity savings of up to 23% by implementing energy efficiency measures. These savings stem mostly from proper lighting use (11%), while only considering improvements in the highest consuming item — air conditioning systems — amounting to a 4% contribution in expected electricity savings.

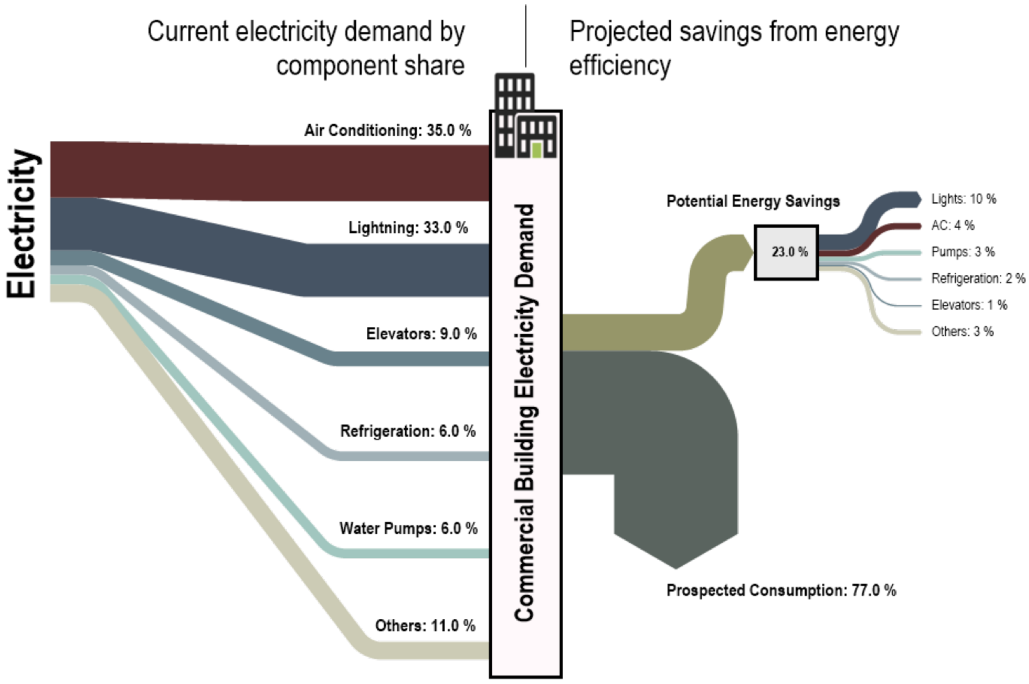

Fig. 1.2.: Sankey diagram showing the electricity demand in commercial buildings by estimated component consumption, along with expected energy savings under more efficient component use [Own illustration, based on MINEM, 2008].

1.2 Peru and Climate Change Actions

The current energy context in Peru has recently been subject to changes because of action related to tackling climate change. As identified in Peru's National Energy Plan (MINEM, 2014), climate change is a central issue in the energy agenda of the country due to the high amounts of greenhouse gas (GHG) emissions currently produced by the energy sector. On this front, the Ministry of Energy and Mines (MINEM) considers measures tackling energy efficiency and renewable energy generation as part of the solutions towards reducing the countries emissions. Similarly, the Ministry of Environment (MINAM) recognizes the Peruvian energy sector as the second-biggest emissions contributor after the transport sector, and thus promotes policies to foster sustainable measures and changes, among other things, in Peru's energy mix (MINAM, 2010).

In this sense, a revision of the current electricity usage, driven in large portions by air conditioning systems, has been identified to reduce both electricity consumption (MINEM, 2008), and the amount of air pollutants released into the environment (Carbon Trust, 2015). At the same time, approaching this specific item in the electricity consumption mix becomes critical when considering an increase in projected temperatures of up to 1.6 °C by the year 2030 in Peru (SENAMHI, 2010). Increased ambient temperatures related to climate change have been predicted to increase the global demand for cooling up to 70% before the end of the century (Labriet et al., 2015), which will increase electricity consumption (Davis and Gertler, 2015), putting greater strain on the electricity supply system. In addition to this, if the average income in Peru keeps on growing at a comparable rate to what it has been doing in the last two decades (IMF, 2015), this might lead to the even greater adoption of air conditioners (Davis and Gertler, 2015). The city of Lima already sustains high air pollution levels and air quality well below the regional average (EIU, 2010; Liebenthal and Salvemini, 2011), which will only be exacerbated if air conditioning use grows, by other environmental factors such as the heat island effect (Lundgren and Kjellstrom, 2013). This problem, paired to the ongoing contribution of emissions by the energy sector, poses as a challenge in Peru's climate change action efforts (MINAM, 2010).

The need to implement high efficiency, alternative cooling solutions to conventional air conditioning systems becomes apparent under this context. Thus, alternatives such as district cooling, which has proven successful in reducing energy consumption, emissions, and pollution (UNEP, 2015); could pose as a potential energy efficiency solution and climate change mitigation tool.

1.3 District Cooling as an Energy Efficient Solution

A district cooling system is a district energy system that distributes chilled water, or another chilled fluid, to end users (Gang et al., 2016; Olama, 2017). The end users can then use the chilled water for space cooling instead of using traditional air conditioning units (Gang et al., 2016).

District cooling systems are constructed in a similar way to district heating systems, and their main components can be divided into cold production plants, thermal storage and a distribution network that delivers the cooling medium to the end-users (Gang et al., 2016). Supplementing these parts are various control systems, pumps, filtration systems and other things that are necessary for the functioning of the system (Olama, 2017).

District cooling systems have several advantages over traditional air-conditioning units in buildings. Producing cold in a central plant instead of using distributed air conditioning units utilizes the economics of scale and thus manages to reduce costs (Olama, 2017). Additionally, it might be possible to use off-peak electricity to produce cold and then store it in the district cooling system's thermal storage units. This way the system can benefit from potentially lower off-peak electricity prices and a reduction in peak energy demand (Hasnain, 1998). In general, district cooling systems have the potential to reduce the amount of GHG and pollution that would be produced to supply cooling, while at the same time reducing costs (Rezaie and Rosen, 2012).

Even though district cooling systems have numerous advantages over distributed and central air-conditioning units, there are also substantial disadvantages that need to be considered. Refurbishment costs for buildings that don't have centralized air conditioning systems might be prohibitively expensive in case one were to switch over to a district cooling system. Capital costs for large centralized district cooling systems can also be high compared to the alternatives and might deter people from them (Papageorgiou et al., 2006). Another problem is finding a suitable site for the components of the district cooling system when building it up in a densely populated area (Rezaie and Rosen, 2012). Knowledge of the planning, building, and operation of complex district cooling networks might also be limited in places that don't have any district energy systems already (Rezaie and Rosen, 2012). Finally, even though a district cooling system might be technically feasible, market structures might exist that make the system unfeasible (UNEP, 2015, p.13).

1.4 Problem Statement and Research Questions

As mentioned in the previous sections, worldwide demand for cooling is projected to rise sharply in conjunction with increased ambient temperatures. Adding to this, economic growth in Peru is likely to increase the demand for cooling even more in the coming decades. In the case of Peru, space cooling is already the largest consumer of electricity in the residential and commercial sector and as such negatively contributes to the environment, either directly via the heat island effect or leaking of refrigerants, or indirectly through the usage of electricity produced by fossil fuels. If the usage of air conditioners were to increase significantly, it might exacerbate the aforementioned problems. Based on the issues described above and the fact that the Government of Peru has made energy efficiency in the electricity sector a goal, this thesis report will aim at addressing the following question:

“Is the provision of district cooling in commercial sector buildings in Lima’s financial district a viable alternative under the current context of Peru’s energy efficiency goals?“

To better understand the question mentioned above, it is decomposed into the following subquestions for further analysis:

1. What current policies and institutions could foster, or hinder, the development of district cooling in Lima?
2. What is the current cooling situation in the commercial zone of the San Isidro district in Lima?
3. How should a new district cooling system be designed according to the existing cooling potential in the district?
4. What are the economic cost benefits of a district cooling implementation?
5. What policies suggestions could further the development of a district cooling system in Lima?

Subquestion one is answered in Chapter 4: "Governance Framework", subquestion two will be answered in Chapter 5: "Cooling Situation in San Isidro", and subquestions three and four will be answered, respectively, in Chapter 6: "System Sizing and Costs" and Chapter 7: "Implementation Scenario". Finally, subquestion five will be answered in Chapter 8:"Recommendations and Discussion".

1.4.1 Scope of Study

As stated above, one of the main goals of the project is to identify the potential and barriers for implementing district cooling technologies and policies to address the lack the energy demand for thermal comfort in commercial buildings in Peru. However, the scope of analysis will take a localized approach in Lima’s San Isidro district for practical considerations, since this district is a cluster location for buildings belonging to the targeted sector. Accordingly, only a limited number of relevant district cooling technologies will be considered, along with related policy applications.

Onsite assessments of the building characteristics will not be presented here, and thus the analyses will be conducted based on previous studies and representative characteristics. Nonetheless, the input of local actors is considered for constructing a contextual understanding of the implementation and policy barriers that might be encountered in the process of deploying district cooling.

Besides limiting the scope of the technologies and analyses, the scope is also constrained by other practical considerations; although the implementation of district cooling can be conductive for developing project specifics for consolidating a final business model, the analysis here will present a macro view to construct different options and estimated project valuations. A more detailed description of other practical and conceptual limitations of this project are provided in the following chapters, namely in Section 2.5.2 and in Chapter 3.

1.5 Thesis Report Structure

This thesis report consists of nine main chapters, which are further divided into sections and subsections. These can be summarized as follows:

Chapter 1 — Introduction: The current energy context in Peru will be presented in relation to the commercial and business sector. The initial case for district cooling as an energy efficient alternative to air conditioning systems is presented, followed by the thesis' research question and scope of work.

Chapter 2 — Worldview and Theories: The general theoretical backdrop of this project is presented in this chapter. Considerations related to district cooling in Peru are presented as a literature review, as well as an identification of relevant actors under the Peruvian context. The main theories, premises, and considerations of the study will be elaborated upon, leading to the choice of research design and further identification of limitations.

Chapter 3 — Methods: The analytic techniques used in this study is explained. The data gathering process is described, as well as the analyses used.

Chapter 4 — Governance Framework: The current legal framework in Peru is explained, and contrasted to the local institutional perspective and accounts of local actors. Framework condition barriers for a district cooling implementation are then identified.

Chapter 5 — Cooling Situation in San Isidro: This chapter provides an overview of the local cooling potential in terms of the city's cooling degree-days. A spatial representation, in the form of an energy map, is then outlined to estimate areas with significant cooling density in the target district's commercial zone.

Chapter 6 — System Sizing and Costs: Site selections for potential district cooling plants are examined. This then leads into an analysis of the potential layout of the district cooling distribution network and its related costs. Then, choices of cooling technologies are briefly considered for the complete sizing and costing of the district cooling system.

Chapter 7 — Implementation Scenario: Economic indicators of the district cooling implementation are presented, followed by the identification of a business as usual and a district cooling distribution consumer choice. Each of these is then compared on the basis of their economic performance. Sensitivity analysis of key parameters is also conducted.

Chapter 8 — Recommendations and Discussion: Based on the results of the analysis presented in previous chapters and from modeling, suggestions in the form of policy recommendations are made. The results and limitations of the analysis presented in the thesis report are then discussed.

Chapter 9 — Conclusions: The main observations and conclusions obtained from the topics examined in previous chapters and throughout the project are presented for the purpose of answering the research questions.

Worldview and Theories

2

> *Adequate knowledge is that which is relevant to the aims of the trip...*
>
> — **Frede Hvelplund**
> (Hvelplund, 2001, p.18)

An essential aspect to consider before developing answers to the research questions presented in Section 1.4, is the framework upon which the analysis is based. That is to say, the worldview, theories, and parting premises considered to lay the foundation for the research approach presented in this thesis report. The purpose of this chapter is to present such considerations.

For this, an overview of the current district energy landscape is presented in order identify the state of being of these type of initiatives under a global context. This, in turn, will facilitate the future identification of key aspects, conditions, and steps to follow at a Peruvian level for a transition into the use a district energy. Then, a brief overview of the district cooling technologies will be presented, which will identify the local relevance of some of these for the case at hand. Following this, the argument for undertaking an exploratory case study approach is presented, since this serves as the backbone for considering the San Isidro business district as an area of investigation. Subsequently, the context of initiatives related to district cooling will be discussed and tied back to an overview of the relevant local actors in the Peruvian landscape. Doing so will lay out the grounds for properly identifying in later sections the role and action of potential stakeholders in a district cooling implementation, and the framework under which they operate. Finally, these themes are linked to key considerations that build up the case for the research design approach followed throughout the rest of the report.

2.1 Global District Energy Landscape and Transition

District cooling and its counterpart, district heating, can be viewed in broader terms as district energy systems. The development of commercial district energy as such dates back to the late 1800s, in the form of district heating systems, and since then a natural progression using more efficient technologies has taken place. District cooling developments are — relative to district heating — less widespread, despite the technology being in the global scene for decades. Even so, district heating and cooling already have mature market shares in many cities around the world (Frederiksen and Werner, 2013, pp.241-260).

The vast majority of district energy networks are found in the Northern Hemisphere, namely in Europe, where there is a traditionally strong energy demand for space heating and thus, a widespread adoption of district heating. District cooling has less market penetration, yet many district cooling grids are found in cities throughout the region (Frederiksen and Werner, 2013; Ecofys, 2016). Worldwide, the application of district energy systems under its different forms has also taken deep hold in cities with high energy demand for space heating and cooling. Cities in places such as the United States, Canada, the Gulf countries, Japan, South Korea, and China, to name a few, are expected to expand and increase their current district energy capacities (UNEP, 2015; Olama, 2017). Moreover, the United Nations Environment (UNEP, 2015) identifies a vastly untapped potential for district energy in which district cooling will play an ever increasing role in developing countries and regions such as Asia and Latin America.

The regional panorama for district energy initiatives in Latin America reflects this increasing worldwide interest. Although no projects have been specifically designed in Peruvian cities, neighboring South American countries have recently adopted district energy systems in their city development agendas. This is the case in Chile, where novel residential biomass district heating systems are promoted (Electricidad, 2015; MMA, 2014). Similarly, in Colombia, Medellin's district cooling system has become the first of its kind in the country and the Latin American region (SECO, 2016; EPM, 2016).

In the locations mentioned above, the transition to district energy systems from other sources of heating and cooling has been, to date, driven by many factors. Some of the initial considerations for this transition included the prospect of reducing fire hazards in public buildings, mitigating the impact of high costs of coal, which was used as heating fuel, and reducing the future fuel demands (Frederiksen and Werner, 2013, pp.241-260). Later adoptions of district energy systems came to be as a response to the global fuel crises, and thus became solutions by which governments could exert more self-reliance towards importing fuel for their energy needs (NRC, 1985). The expansion of district heating and cooling is also being used as an option for decarbonizing the energy systems and fostering energy efficiency (Connolly et al., 2012; Ecofys, 2016), lessening the strain in electricity systems (UNEP, 2015), reducing the contribution of ozone depleting substances and GHG emissions (SECO, 2016), reducing costs of existing systems (Connolly et al., 2012; Fayad et al., 2012), increasing thermal comfort, and for mitigating the effects of climate change (Lund et al., 2014; UNEP, 2015; Ecofys, 2016; SECO, 2016).

Although the benefits of transitioning to district energy systems seem readily apparent, it is critical to look at these solutions from a broader perspective so as to not reduce their implications or underlying elements. As discussed by Hvelplund (2001, pp.15-25), an adequate identification of the structures at play is necessary for the process of understanding changes in the energy systems. These "*adequate structures*", Hvelplund elaborates, are constituted by the societal, institutional and governances systems; and the characteristics and dynamics among these. Moreover, a long and short-term time horizon is suggested to prevent short-sightedness in constructing an understanding of changes in the energy system and the aforementioned underlying structures.

Similarly, in discussing the future of district heating and cooling Frederiksen and Werner (2013) identify a level of uncertainty in long-term planning for this energy transition that can be counter by expanding the understanding of the underlying elements contributing to changes in the energy system. In relation to the above, Frederiksen and Werner (2013) suggest that building a definition of the structure of the future district energy system and its features, along with identifying aspects of the existing system that align to the new systems in transition, are conductive to identifying what needs to be adapted and changed for the transition to take place.

It can thus be argued from these considerations that examining the locational features of the district under analysis and the governance framework in Peru is necessary to understand the implications of developing a district energy transition in Peruvian cities. This, in turn, needs to converge with a detailed understanding of district energy systems as such, and with undergoing initiatives with which the proposed system will have to adapt to or compete against.

2.2 Overview of District Cooling Technologies

Various options for supplying cold are commercially available for use in district cooling plants. These are broadly divided according to their function, either for cold generation or cold storage. Accordingly, this section presents a general description of the relevant plant technologies considered for the project of the district cooling implementation in San Isidro.

2.2.1 Vapor Compression Chillers

Vapor compression chillers are one of the most common types of chillers used in district cooling projects (Frederiksen and Werner, 2013). They are the same type of chillers usually found in refrigerators and air conditioning systems and are powered by mechanical power that can be supplied with electric motors. These coolers are either air or water cooled, but water cooled versions have greater efficiency than air cooled (Olama, 2017).

2.2.2 Absorption Compression Chillers

Absorption chillers use heat instead of mechanical power to drive the refrigeration process and as such can use various sources of heat to run. Absorption chillers can be run directly by burning gas or other fossil fuels, but the process can also be run using waste heat from power plants or other industrial processes (Frederiksen and Werner, 2013).

2.2.3 Free Cooling

Free cooling utilizes cold sources in the environment to cool down water for district cooling. These sources can be a lake, a river, ground water or even sea water, and if cooling sources are cold enough, no extra power is needed besides pumping power (Frederiksen and Werner, 2013). Where free cooling is available, it is usually the cheapest option because it is not necessary to spend energy on cooling down water. However, some of the limiting factors of this technology are the distance from the source to the plants and buildings to which chilled water is distributed (AREA, 2014), and source water temperatures, which need to be lower than cooling water temperatures in the system to properly operate (Bomholt, 2004), .

2.2.4 Thermal Energy Storage

Thermal energy storage (TES) acts as a cold reserve supply, which allows shifting cooling energy loads from peak demand hours, or sudden load changes, to lower demand periods. This, in turn, allows for plants to be sized with lower chiller capacities since storage covers the load not met by the cooling generation equipment, thus reducing chiller equipment investment. Additionally, the storage reserves may serve as a buffer in cases of cold generation shutdowns (IEA, 2002a; Frederiksen and Werner, 2013). Many TES technologies exist, though chilled water storage is the most widely used because of its cost effectiveness, high specific heat capacity, simplicity of use, and flexibility to plant retrofits (Phetteplace et al., 2013).

2.2.5 Local Relevance of Technologies

As seen so far, a number of technologies can apply to district cooling plants. However, some limiting factors must be brought into consideration for the plant and storage selection in the potential implementation case in San Isidro.

The cold generation options mentioned in the previous sections require different energy or cool sources to operate. In the case of vapor compression chillers, electricity is readily available throughout the San Isidro district, thus allowing the operations of vapor compression chillers, in the form of electric chillers. Likewise, absorption chillers are considered due to the availability of gas distribution near San Isidro's commercial zone (Calidda, 2017), which could provide fuel for this type of technology.

On the other hand, free cooling sources are not readily available. As is discussed in Section 6.3.4, access to sea water is not adjacent to the district's commercial zones, and thus requires several kilometers of piping to be laid across the district, through residential areas, to serve the target commercial zones. This, in turn, poses as major investment hurdle when considering this cooling technology option. Moreover, superficial sea water temperatures, averaging around 18.3°C throughout the year (SeaTemperature, 2017), may not be an adequate source for chilled water, consequently resulting in further need for deep sea water as an appropriate cooling source (Looney and Oney, 2007), and a more considerable investment to accompany this solution.

For the case of TES, the option of chill water storage provides benefits befitting the implementation of district cooling in San Isidro. However, a major hurdle to consider is the potentially significant areal footprint of this type of technology. Other TES technologies, namely ice storage are more compact and more modular solutions than chilled water storage. However, their use may be mostly limited to small implementations, since this storage technology does not provide economy-of-scale benefits in larger implementations (Phetteplace et al., 2013), which is expected in the latter phases, introduced in Section 6.2, of this district cooling implementation.

2.3 San Isidro as the Area of Study

In developing a district energy plan, the name coined for the technology itself is highly suggestive of its area of implementation at a district level. Focusing on dense areas, like business districts, is often preferable for deploying a district heating or cooling project due to the high potential for covering the existing high energy demands present in these areas (UNEP, 2015, p.53). Moreover, by focusing initially on these areas, the economics of the project can rely on less intensive amounts of capital investment than would otherwise be needed for less dense energy demand spots (Frederiksen and Werner, 2013, p.526). As explored in UNEP's *District Energy in Cities* report (UNEP, 2015, p.106), these initial localized approaches can then lead into subsequent development phases over long project development periods.

In a broader sense, the selection of the San Isidro district is also related to underlying considerations. This location may be linked back to the concept of an "adequate structure" explored by Hvelplund (2001), as mentioned in Section 2.1. The identification of this area of study serves as such a structure in the sense that the stakeholders and prospective energy plans act within the confines of the district and its specific framework conditions.

Parting from the aforementioned considerations, the development of a district cooling strategy in San Isidro also acts as a case for the process of answering the research questions posed in Section 1.4. The general context of San Isidro is not necessarily representative of the average district in Peru due to the high number of businesses, offices, institutional approaches, and greater than Peruvian average living standards (Avilez et al., 2011, p.18). Nonetheless, by merit of the specific characteristics attributed to the district, the examination of the specific framework conditions for deploying district cooling in San Isidro serve as a critical case.

As defined by Flyvbjerg (2006), a selection of a critical case takes as basis maximizing the gain of information by strategically selecting the sample under study to make generalizations. In more specific terms, San Isidro was chosen based on prior knowledge of its characteristics; and, if district cooling were to work in San Isidro, it could likely work in districts with similar framework conditions.

A key driver behind case generalization stems from the fact that the decision-making process in Peru is not self-contained at a district level, but rather it is constituted by the engagement of a number of local, regional and national institutions and actors (Mcnulty, 2013). Inasmuch as other actors are concerned, the potential of rolling out the outcomes of a district cooling project to other locations becomes more relevant in the policy process. Similarly, to the extent that the case of district cooling in San Isidro treads uncharted waters, the case generalization serves as a way to develop a different line of thought. This exploratory case approach is conductive to evaluate the many potential outcomes that might arise (Baxter and Jack, 2008). This is turn adds nuance to the current paradigm of the local energy planning process, thereby potentially acting as a paradigmatic case, or as examined by Flyvbjerg (2006), a case that could set a standard.

Notwithstanding these classifications, the case can arguably take other overlapping tints. Given the distinct characteristics of San Isidro when compared to other districts at the national level, it could arguably be considered more of an outlier, or extreme case as per Flyvbjerg's definitions. In this regard, Olsen et al. (2014) caution that such a "purposive site selection" approach lends itself for more narrow or less rigorous generalizations. Hence, the validity of generalizing from such a strategic case selection should be viewed with caution. The replicability of a San Isidro district cooling project should then be treated in terms of the extent to which it applies to other selected districts under the current conditions and the adequate structures in place.

2.4 Initiatives and Institutions

Viewed broadly, the development of district cooling is strongly tied to government actions and project developers' approaches to cover potential cooling demand in buildings (Fayad et al., 2012). These considerations apply when looking at policy interventions that foster new project developments (UNEP, 2015).

In this regard, the role of both national and local authorities in these interventions has been found to be key to the promotion of district heating and cooling initiatives (UNEP, 2015; Galindo Fernandez et al., 2016). The government actions to be considered can be wide-ranging. As explored in Section 2.1, many reasons can drive the transition towards district cooling systems. This, in turn, may translate into national policies related to energy efficiency, resilience and energy security, decarbonization, air pollution, and climate change; according to the context area. In a similar manner, the role of the local governments must be accounted for. The participation of local governments has been identified as a cornerstone in developing district energy projects (UNEP, 2015); thus, the role of the San Isidro Municipality is also central in this process. In this sense, the actions of the municipality have to be viewed in an institutional context where sustainability issues are a relatively new development in the local government's agenda (MSI, 2015b).

Similar to the intervention areas mentioned above, the new and existing buildings' energy demands to be integrated into district energy project need to be considered (Lund et al., 2014), along with the choices of construction developers to follow suit with this or other cooling approach based on the existing framework conditions (Fayad et al., 2012). The latter aspect can be related back to sustainable construction approaches, which may go as far as taking for granted the connection to district energy networks (CPH Cleantech, 2013). In more general terms though, the integration of energy efficient buildings has been deemed instrumental for cost effectiveness in the transition of new district energy developments (Mathiesen et al., 2016). Likewise, the role and cooperation with construction or real estate developers has been found to be necessary for securing the benefits of developing district energy systems (Galindo Fernandez et al., 2016). Thus, identifying cooperation structures between government institutions and construction developers becomes key for planning district cooling in San Isidro.

In Peru, institutional measures towards achieving sustainable building construction standards are not deep rooted (Miranda and Marulanda, 2002). Peru's first "Sustainable Building Code" was enacted in 2015, having as top priority energy efficiency at a building level, along with water use (MVCS, 2015b). The Sustainable Construction Code came to being as an inter-institutional effort encompassing governmental institutions in different sectors and interest groups (MVCS, 2015a). This cooperation group, formally referred to as the Permanent Committee on Sustainable Construction (PCSC), officially consists of

14 entities with distinct areas of competency. These institutions can be grouped broadly as follows (MVCS, 2015a):

- National Government
- Commercial Groups (Construction Developers)
- Civil Society

The role of the PCSC's members becomes relevant to the case of district cooling since they pose as participatory institutions in the policy-making decision process. In particular, the inclusion of corporate and civil society organizations has been identified as a part of the participatory governance design in Peru (Mcnulty, 2013). The participation of these base governance structure with already define energy efficiency competencies, thus, could arguably catapult district energy developments for new and existing building stock.

Parallel to the government institutions and the actors related to energy efficiency through the sustainable construction sector, other actors with interests in this matter exist. As identified by Ghosh Banerjee et al. (2016), the role of energy utilities can be critical in energy efficiency initiatives. However, their financial bottom line is not always in line with the above unless regulation or policy mechanisms are in place (Ghosh Banerjee et al., 2016). On the other hand, the end-users must also be made aware of the benefits entailed by energy efficiency initiatives like district cooling (CCO, 2014). Consequently, the regulations and policy interventions coming from the national and local government levels should engage the local actors in the decision-making process.

In view of all the actors related to energy efficiency and sustainable construction that could potentially have a part in developing district cooling in San Isidro, and more broadly in Peru, it is important to highlight those with most clear relevance. This identification is further elaborated in Chapter 4, leading to a more in-depth overview of their specific roles and the framework conditions under which they operate.

2.5 Premises and Research Framework

Taking as point of departure the facts and theoretical aspects presented throughout previous sections, a number of parting premises and considerations are taken as base for constructing a suitable research design. This, in turn, will ease the selection of different methods and analyses used to address the research questions of this thesis report. With that goal in mind, the following premises is briefly outlined:

- *Identification of adequate institutional structures*
  As elaborated in Section 2.1 and briefly explored in Section 2.4, assessing the relevance of the institutions related to the case of a district cooling system in San

Isidro is necessary for understanding the effects of transitioning into said system. Moreover, the identification of their roles and dynamics can facilitate the process of identifying working structures and new structures needed, in the form of existing policy, interest groups and new policy interventions. As explored in Section 2.4, government institutions, commercial actors in the construction and energy sector, and civil society have a stake in potential developments of district cooling; and thus, should be included in this analysis.

- *Identification of the adequate system structure and its features*
  As mentioned in Sections 2.1, the district cooling system and its feature must be defined, considering the existing features in place. The confluence of the new and existing systems must be assessed to identify what needs to be adapted and changed. For instances, the existing technologies must be compared to district cooling and its features.
- *Adequate time horizon*
  A long-term time horizon, as suggested in Sections 2.1, should be considered to build a better insight into the implications of transitioning towards a district cooling system. Likewise, a short time horizon should be considered to analyze present dynamics.
- *Critical case selection and replicability*
  The selection of San Isidro as the area of study serves to build a case study around what a district cooling implementation in Peru might be. This selection, as mentioned in Section 2.3 is made upon pre-conditions met in the San Isidro district. Although these conditions guide the strategic selection of San Isidro as area of study, the replicability of this case might only cover districts meeting similar framework conditions. Hence, the generalization of district cooling in San Isidro and related national policy implications are bounded only by specific relevant areas.

2.5.1 Research Design

Proceeding from the premises considered above, the analyses for evaluating the research questions in Section 1.4 is approached from many angles. For instance, the identification of institutional structures might be conductive to assess their adequacy through corresponding elements in the literature and local examination of official documents and personal experiences. The same may apply when considering the replicability of the case study when evaluating the barriers and potential of replicability to other application sectors or locations. On the other hand, identifying the adequacy of the system features can be more accurately represented through proper modeling and spatial identification on a district-wide scale. Likewise, the lifetime of the potential district cooling systems can be better assessed through different deterministic scenarios. Because of the above, this thesis study presents both a qualitative research approach to understand the effectiveness of current policies and institutions, and a quantitative research approach to analyze the technical considerations of the problem and as result estimate costs and impacts of prospective solution alternatives.

2.5.2 Limitations

Due to the scope of the project, it is necessary to limit somewhat the depth in which the different possible technologies are analyzed. Three main groups of cooling technology are analyzed in this report; vapor compression cooling, absorption cooling and free cooling, but all these groups contain a variety of different technologies within them that, although sharing key similarities, have some differences. This report contrast the main differences between those groups of technology and points and tries to determine which groups are preferable over others but does not consider different variations within the groups themselves.

In a similar manner to the analysis of the cooling method, the analysis of thermal energy storage is limited to looking at a system that contains either different levels of chilled water based storage or no storage at all. Other types of thermal energy storage such as ice, or ice slurry are not considered as these kinds of technologies require different types of generation and transportation mechanism and are not as common as water based systems.

3 Methods

This chapter will cover the methods used in this thesis to answer the research questions laid out in Chapter 1.4. The chapter starts by describing the qualitative methods employed for analyzing the framework of the project, identifying stakeholders and understanding better the policies that can affect a district cooling system in Peru. Following that, the methods of modeling and analyzing a district cooling system from a technical standpoint are discussed, and finally, there is a discussion of the method of business-economic analysis.

3.1 Data Collection

3.1.1 Literature Review

Sources in the available literature were examined in order to gain a better understanding of the topics covered in this thesis. This focused on two main topics; district energy policy in general, and in Peru specifically; and district cooling technology. Other themes that were also explored were the effect of climate change on cooling demand and district energy, cooling demand mapping and the design of district cooling systems. The identification of sources in the literature was performed by searching research and library databases, and search engines for keywords that were connected to the relevant topics. For some of the themes in the specific case of Peru and Lima, Peruvian government websites were searched for relevant data, as other sources gave limited results. This search was conducted in both English and Spanish, since a great deal of the literature dealing with Peru are official government reports available only in Spanish.

3.1.2 Interviews

In order to gain better understanding of the institutional framework in which this project is working within, a series of interviews were conducted with key actors. These interviews took the form of semi-structured interviews, where a pre-defined set of topics was used to vaguely guide the interview, while the interviewee was given full freedom to go off topic, and the interviewers followed up on interesting points that emerged during the interview. The interviews were both conducted in person, via telephone and via the internet.

The reason for using qualitative interviews to gather information is the flexibility of the approach and the lack of literature specific to the case of Peru and Lima. Kuada (2012) argues that qualitative interviews offer a change to gain new understanding of a subject matter where theoretical knowledge is lacking. He then goes on to state that the data gathered using qualitative interviews can then be contrasted to the existing theories, often producing new knowledge.

The qualitative interviews conducted leaned heavily towards being semi-structured interviews, as opposed to unstructured. The reason for choosing semi-structured interviews is that they offer great flexibility, while at the same time offer a certain degree of consistency in the topics between different interviews. In a semi-structured interview the interviewers have a list of specific topics they want to discuss, while at the same time allowing the interviewee considerable freedom to respond and veer off the topics (Bryman, 2012). This is in contrast to unstructured interviews which might be more similar to a conversation, where the discussion is maybe just about one topic (Bryman, 2012).

Interviews were conducted with a wide variety of experts from international and local organizations, public corporations and the government, in order to get the broadest possible view on the subject matter.

An adviser on sustainable energy for United Nations Environment was contacted because of his expertise in the field of district energy policy and offered valuable information about the proliferation of district energy in emerging markets.

Several of the interviewees worked for different Peruvian ministries. A specialist at the Office of Cooperations and International Business at the Ministry of the Environment of Peru (MINAM) who also sits on the Permanent Committee for Sustainable Construction on behalf of MINAM alongside the chairman of the Permanent Committee for Sustainable construction, and sits on the committee on behalf of the Ministry of Housing, Construction and Sanitation. They were chosen because of their work within the Permanent Committee on rules and regulations regarding sustainable building codes and energy efficiency.

An Energy Efficiency NAMA Project Coordinator at the Ministry of Energy and Mines of Peru (MINEM) was interviewed because of her knowledge about energy efficiency projects within Peru and the Peruvian energy sector in general.

The CEO of the Peru Green Building Council, a non-profit organization that promotes sustainability in construction and awards various certifications was contacted in order to provide a different perspective on the state of sustainable construction and energy efficiency measures in Peru.

A meeting was held with the Department of Sustainability of San Isidro municipality. Attending the meeting were three employees of the department. The meeting with the municipality offered a viewpoint on the sustainability measures being taken at a local level and the relationship dynamics between the local and national governments.

Two United Nations experts on district energy networks were interviewed because of their knowledge of district cooling systems and their experiences of different projects from a wide variety of different countries.

Finally, a manager at the Copenhagen district energy company, HOFOR, was interviewed in order to get a perspective on their experience with running their district cooling system in Copenhagen.

3.1.3 Databases and Quantitative Information

Other data sources examined included spatial data of the target commercial buildings in the district for the purpose of conducting energy mapping and related estimates, which will be further elaborated in 3.4. This information included online maps rendered through the QGIS geographic information system software, and total construction areas of buildings, extracted from open map databases. Additionally, floored areas and the number of floors of commercial and public buildings in the SRZ and MCZ were obtained from online databases (SkyscrapperPage, 2017). This information corresponded to dozens of high rise commercial buildings, out of the 223 total buildings identified. Official data sources were consulted for this information, however no consolidated database was made available at the local level.

3.2 Policy and Interview Analysis

The policy initiatives and the relevant institutions mentioned in Section 2.4 are bound together with the existing legal framework imposed by the Peruvian Government. Hence, an overview is presented in Chapter 4 with the relevant policies connected to the case of a potential development of district cooling, based on the information collected from governmental reports.

The aforementioned information was then analyzed under the relevant institutional context, by contrasting the policy application with the real accounts of local institutional actors gathered through interviews, as mentioned in Section 3.1.2. Key themes found in the passages of the collected governmental information and interview transcripts were then categorized with the qualitative analysis software NVivo. As discussed by Fischer et al. (2007), qualitative text analysis applications provide a way to systematically approach the categorization of patterns and relationships found in texts. Thematic threads found in the different sources of information were categorized in NVivo, with specific topics across the different sources grouped as common nodes. The specific topics found across the different governmental texts, and interview sources were linked together according to their thematic relationship, for ease and consistency in the analysis.

The thematic analysis of policies and institutions in turn, provide a better understanding of the governance structures and the identification of policy implementation barriers and potential opportunities that might be encountered in developing district cooling in San Isidro. Subsequently, this identification of both institutional barriers and opportunities will be tied back in Chapter 8 with the results obtained in Chapters 5 and 6, in the form of a discussion about the results and recommendations.

3.3 Cooling Degree Days and Hours

Cooling degree-days and degree-hours were used when estimating the cooling energy demand, and comparing the cooling situation in Lima to other cities. Cooling degree-hours (CDHs) measure the difference between the outdoor temperature and an indoor base temperature over a period of one hour while cooling degree-days (CDDs) measure the same temperature difference over a period of a day. The equation for CDHs can be given as

$$D_{h,j} = (\theta_{o,j} - \theta_b)_{(\theta_{o,j} - \theta_b) > 0} \tag{3.1}$$

were $D_{h,j}$ is the cooling degree hours in hour j, $\theta_{o,j}$ is the outdoor temperature in hour j and θ_b is the base temperature (CIBSE, 2006). Cooling degree-days can be calculated by calculating the average cooling degree-hours for a 24 hour period. The equation for for CDDs is given as

$$D_d = \frac{\sum_{j=1}^{24}(D_{h,j})}{24} \tag{3.2}$$

where D_d are the cooling degree day(s) for a day (CIBSE, 2006). In the case of this report, the base temperature used was 18.3°C as stipulated by the ASHRAE Fundamentals handbook when it comes to HVAC systems (ASHRAE, 2013c).

3.4 Cooling Capacity Mapping

A mapping of the estimated current cooling capacity in San Isidro was conducted in order to locate potential demand hotspots, and thus tentative locations for a district cooling network. In the absence of data about the cooling demand for the district, it was decided to use the installed cooling capacity as a proxy for the demand. It is assumed that buildings in the areas targeted in San Isidro have cooling systems that are designed so that they cover peak demand as stipulated in the ASHRAE design conditions for HVAC systems. It is thus assumed that if the cooling capacity of a building is known, the peak cooling demand of that building is also known. The estimated cooling capacity of buildings was then used to design load profiles for the buildings in the district.

The cooling capacity mapping was split into two parts, the first one was to estimate the floor area of buildings in the SRZ and the MCZ of San Isidro that required cooling, and the second was to determine the current cooling capacity per square meter for the buildings in those zones. This data was then combined in order to create a map of the cooling capacity density. This method is recommended by Cornelis and Meinke-Hubeny (2015) to estimate the demand in the case of areas with an abundance of commercial buildings.

To estimate the floor area, a map of the current structures in the district was required. After failing to locate a database specific to San Isidro that contained outlines of buildings it was decided to use openly available map data from the OpenStreetMap project. OpenStreetMap is a community driven mapping project, utilizing volunteers to provide geographical data. The maps are licensed using the Open Data Commons Open Database License that allows for open and free use of the database (*OpenStreetMap* 2017). A map of the various building zones in San Isidro district (Figure 3.1) was acquired from the San Isidro municipality in order to identify which buildings are in the Metropolitan Commercial and Special Regulatory Zones. Using the above mentioned maps and the open-source geographic information system software QGIS, the outlines of buildings within the metropolitan commercial zone of San Isidro were drawn. The outlines of the buildings were verified using satellite and 3D model data from Google Maps and Google Earth and in some cases corrected based on this information. In order to determine total floor area based on the land area of each building the number of floors for each building was determined using the SkyscrapperPage database (SkyscrapperPage, 2017) in conjunction with the Street View feature of Google Maps.

It was necessary to figure out the peak cooling capacity per square meter of floor area so that the total cooling capacity of each building could be calculated. Because of lack of data regarding building cooling demand or capacities in Peru, it was decided to use data from places with comparable climate conditions and relate their cooling demand or capacities to those of Lima. The ASHRAE Handbook ASHRAE (2013c) contains design parameters and conditions to use when designing HVAC systems for buildings. In these guidelines the 0.4%, 1.0% and 2.0% top percentile temperatures for a location over a year are used to aid in the design process of air conditioning systems, and these parameters were used as criteria to find cities that could correspond to Lima when it comes to peak cooling capacity. The ENTRANZE project seeks to analyze heating and cooling loads for various European cities, and has data regarding cooling load for Seville, Madrid, Rome, Milan, Bucharest, Vienna, Paris, Prague, Berlin and Helsinki. Comparing the ASHRAE parameters for Lima to these cities shows that the cities corresponding the most to Lima are Berlin and Prague in terms of peak design temperatures. Table 3.1 shows a comparison of the top 0.4%, 1.0% and 2.0% percentile temperatures in these cities to those of Lima. Looking at the energy demand for cooling in commercial and office buildings during peak load revealed that it is about 40 W/m2 (Zangheri et al., 2014) for Berlin and Prague. It is thus assumed that the peak cooling demand in Lima will also be 40 W/m2, since it is assumed that the HVAC systems in Lima are designed around these same parameters. It is also assumed that this peak demand in the cases of all the cities considered corresponds to the installed air conditioning capacity.

The method described above does not consider other factors necessary for an accurate estimate of cooling demand or installed cooling capacity beside temperature, such as building envelope characteristics, since such an analysis and comparison with other cities would be time consuming and beyond the scope of this project. However, there is currently an overall trend in Peru towards building high-end offices according to international sustainability standards (PeruGBC, personal communication, 2. March, 2017) and as such it is reasonable to assume that the characteristics of the buildings in the metropolitan commercial zone of San Isidro are comparable to buildings in Berlin and Prague.

Tab. 3.1.: The top 0.4%, 1.0% and 2.0% percentile temperatures in the year 2013 for the cities of Lima, Berlin and Prague (ASHRAE, 2013a)

	0.4%	1.0%	2.0 %
Lima	28.9°C	27.8°C	26.9°C
Berlin	29.3°C	27.3°C	25.6°C
Prague	30.3°C	28.3°C	26.5°C

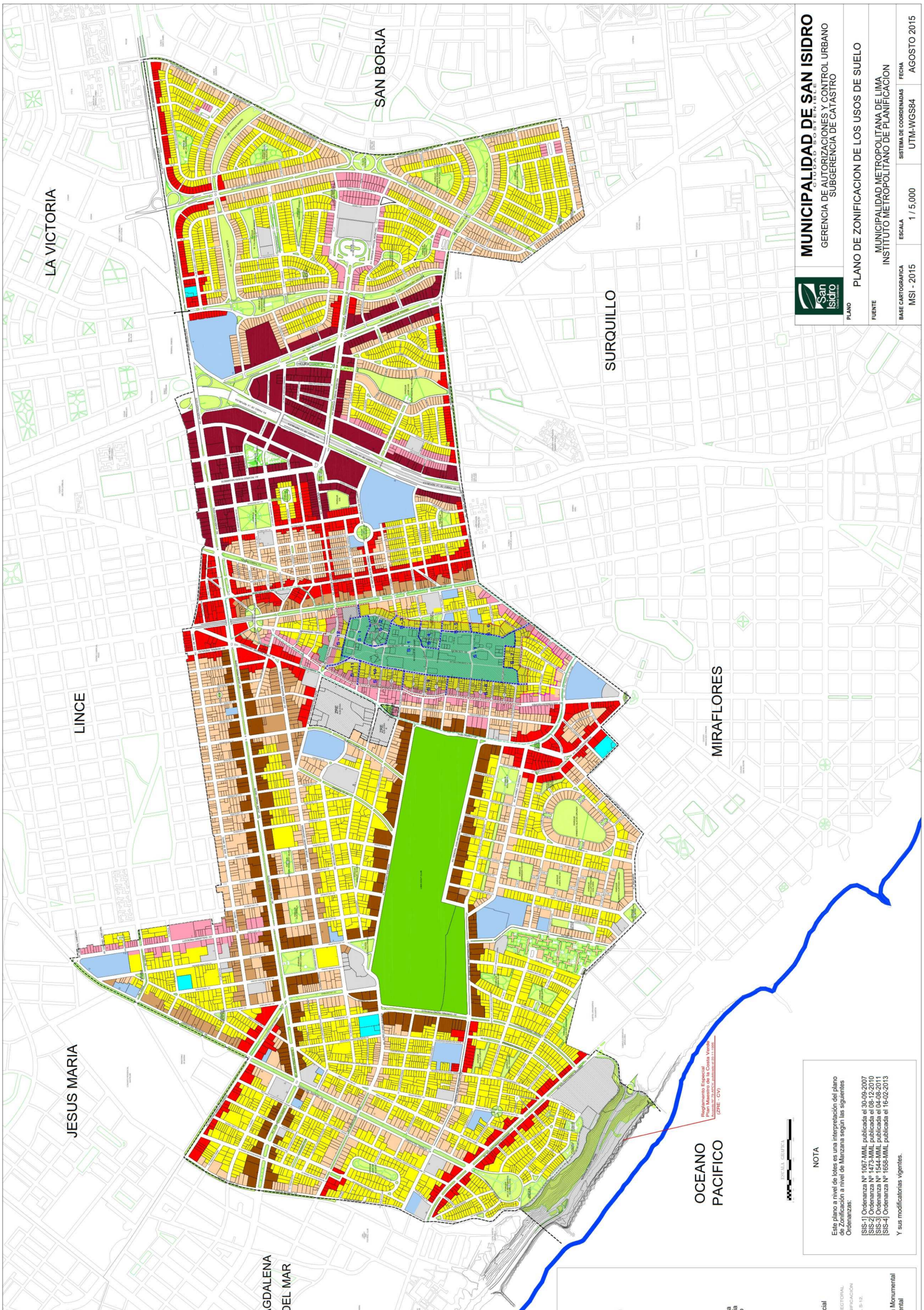

Fig. 3.1.: A map of the different zones of San Isidro municipality (Source: MSI (2015a))

3.5 Cooling Load Estimates

Cooling load profiles were created for usage in the technical and economic simulation by combining ambient temperature data, estimated base load and occupancy hours of the target buildings.

When constructing the cooling load for San Isidro district the cooling degree hours in Lima were used as an indicator of hourly fluctuations in cooling demand. Cooling degree days and hours are indicators of energy demand for cooling in buildings (De Rosa et al., 2014) and thus a useful proxy in the absence of actual cooling energy demand data. It should be noted, however, that the connection between outdoor temperatures – and consequently CDHs – and cooling energy demand is in reality complex and heavily dependent on building characteristics, such as the thermal inertia and the internal heat gain of a building (De Rosa et al., 2014). To construct such an accurate cooling energy demand profile would thus require a thorough analysis of each building in San Isidro, which is not feasible for this project. Thus, this report assumes for simplification that there is a simple linear correlation between CDHs and the cooling energy demand.

In chapter 3.4 it is determined that the current cooling capacity and thus the maximum cooling demand of buildings covered in this project is 40 W/m2. This means that when the buildings are exposed to their maximum design temperature conditions they should be running at maximum capacity, which thus corresponds to maximum demand. Using this knowledge the CDH data for Lima was thus normalized using the top 0.4 percentile annual CDHs as stipulated ASHRAE design conditions (ASHRAE, 2013c). Using 2016 as a refernece reference year this corresponds to putting the load at 100% when the CDHs reach 10.86°C while the maximum annual CDHs are 13.09°C. Figure 3.2 shows the normalized cooling load hours which the cooling load was assumed to follow.

During the capacity mapping in the previous chapter, two different types of institutions were identified as occupying buildings in the SRZ and MCZ. These were offices and hotels, and each of those two building types needed a different load profile to represent when the buildings are occupied and, thus, when there is demand for cooling, and what the base load cooling is in each type of building. To determine the occupancy hours of offices in San Isidro, Google Maps was used to extract information about opening and closing times, and this indicates that the general working office hours are from 8:00 in the morning to 18:00 in the afternoon during weekdays, while offices are generally closed during the weekend. To further corroborate this, statistics from the International Labour Organization (2007) indicate that the average working week in Peru is 49.3 hours, corresponding to 9.8 hours for five days per week. Hotels were assumed to be occupied for 24 hours per day, all days of the week.

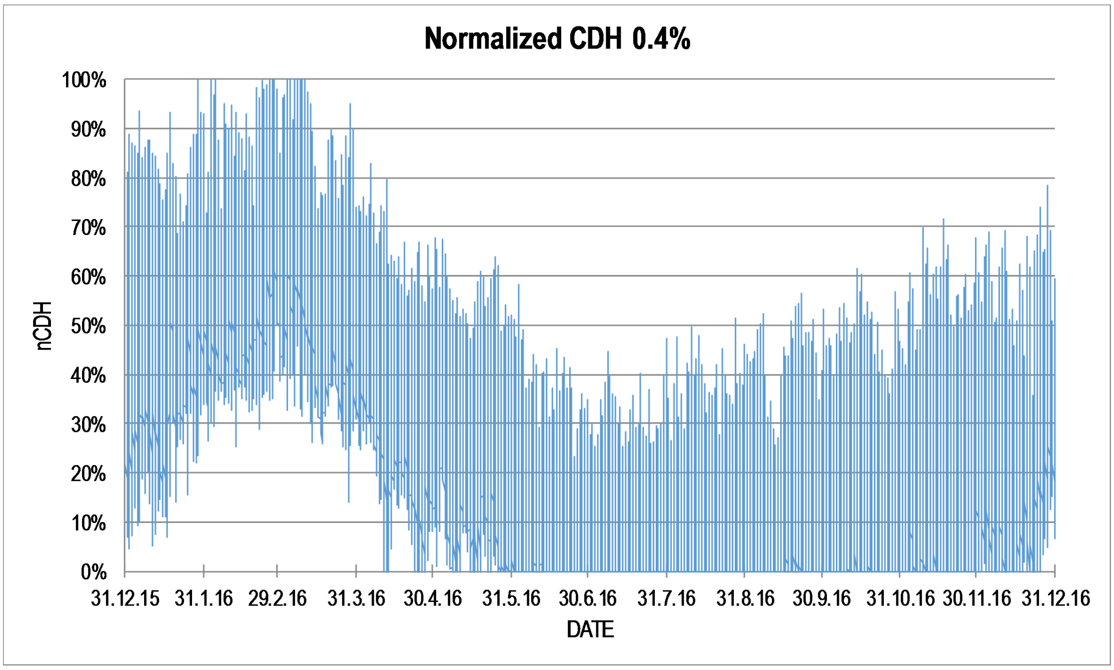

Fig. 3.2.: Cooling degree hours for the reference year 2016 normalized with regards to the top 0.4% annual temperature

In addition to considering the ambient temperature effects and the occupancy hours of both types of building use, the base cooling load was also determined and integrated into the load profiles. This meant that the energy demand of a certain building will never drop below the base load. Lam et al. (2003) present the energy and cooling demand of four office buildings in, and these demand patterns were used to find out that the base load cooling demand for those buildings as a percentage of average demand during occupancy hours, is 9.5%. In the absence of other data, the base load of hotels was considered to be the same as the office base load. Table 3.2 gives an overview of occupancy hours and base load for the different types of building use in San Isidro.

Tab. 3.2.: Occupancy hours and base load for offices and hotels

	Office	Hotel
Occupancy - Weekdays	8:00 - 18:00	All day
Occupancy - Weekends	Closed	All day
Base load	9.5%	

From the above data it was possible to construct load profiles for the different phases of the district cooling development. These load profiles served as the base for the analysis described in Section 3.6.7, and are furthered described with in Section 6.4.

3.5.1 Reference Year

As covered in Chapter 1, the expected trend in average temperatures in Peru is upwards, and they are expected to rise up to 1.6°C by the year 2030 (SENAMHI, 2010). The fact that temperatures are predicted to rise in the near future, coupled with the fact that there has been a trend of warmer subsequent years over the last decade (INEI, 2016), led to the decision to use data for the warmest year average year this decade, 2016, as a reference year. The approach of using 2016 as a reference year, instead of finding a more average year for the past decade, offers a certain degree of assurance that the system designed will be capable of tolerating expected elevations in temperature over the lifetime of the project.

3.6 System Design

3.6.1 Phased Approach

It was decided based on interviews and the literature that a phased approach to the system design would be the most natural way for the district cooling system to be implemented. During an interview with UNEP experts they agreed that the usual approach to developing a district cooling system would be to do so in multiple phases, as opposite to developing and implementing a large (district wide) system in one stage (UNEP experts, personal communication, 4. April 2016). Frederiksen and Werner (2013) also present typical growth structures for district energy systems, where they show how these systems initially start small but later grow to become large interconnected systems. Based on this it was decided to split the project up into a couple of major phases that will be introduced in later chapters.

3.6.2 Distribution Network

Since the area being targeted for this district cooling system is relatively small the approach towards designing the phases was to plan the reach of the last phase of the project first, and then work backwards to a predetermined initial phase of the project. This way it was possible to design the distribution network in such a way that the the layout and the capacity of the pipes would take into consideration the location and demand of the buildings in the final phase. When the layout of the system for the final phase of the project was clear, the layout for earlier phases were made, in conjunction with selecting which buildings would be included in those phases.

The design of the distribution network was conducted using the geographical information system software QGIS, and was done in conjunction with the development of the different phases of the project. Using the software it was possible to trace the paths for distribution pipes as well as determine their required capacities based on the cooling demand for areas and building they are supposed to supply.

3.6.3 Pipe Sizing

After the pipeline network had been routed it was necessary to determine the size of individual pipes, that is the diameter, in order to assess the cost of the network. According to Frederiksen and Werner (2013) sizing of district energy pipes is an "extremely complex issue", that can be helped with the usage of mathematical optimization models; but even such models "cannot provide definite answers" (Frederiksen and Werner, 2013). In order to simplify the calculations to keep within the scope of this project, certain assumptions regarding the design of the distribution network were thus made.

The cooling power transferred in a piping system is given by the equation

$$\Phi = c_p \rho V' \Delta T \tag{3.3}$$

where Φ is the cooling power, c_p is the specific heat capacity of water, ρ is the density of water, V' is the volume flow rate and ΔT is the temperature difference in the distribution network between the supply and return temperatures (Lahdelma, 2015). The volume flow rate V' is related to the diameter of the transfer pipe, d, by

$$V' = \frac{V}{t} = \frac{Al}{t} = \frac{\pi \left(\frac{d}{2}\right)^2 l}{t} = \pi \left(\frac{d}{2}\right)^2 \mathrm{v} \tag{3.4}$$

where V is volume, t is time, A is the pipe cross sectional area, l is the width of the portion of the fluid under consideration, v is the flow velocity of the water in the pipe. Inserting equation 3.4 into 3.3 and solving for the diameter gives us

$$\Phi = c_p \rho \pi \left(\tfrac{d}{2}\right)^2 \mathrm{v} \tag{3.5}$$

$$d = 2\sqrt{\tfrac{\Phi}{c_p \rho \Delta T \pi \mathrm{v}}} \tag{3.6}$$

The specific heat capacity and the density of water are dependent on the water temperature, with the specific heat capacity ranging from 4205 J/kgK at 4°C to 4189 J/kgK at 12°C while the density of water ranges from 1000 kg/m3 at 4°C to 999.6 kg/m3 at 12°C (Therm Excel, 2003). Since the variations are relatively minuscule for the temperature range that the system is operating on, the specific heat capacity was considered constant at 4200 J/kgK and the density of water at 1000 kg/m3.

Flow velocity is generally affected by friction effects in the pipes which are again dependent on the pipe material and volume flow rate, amongst other things. As a simplification, the flow velocity is assumed to be 2 m/s for this project as this corresponds to a typical flow velocity as presented by Frederiksen and Werner (2013). The temperature difference between supply and return is 8°C.

With the above information it was possible to calculate the minimum diameter required of the pipes so they could supply the cooling demand. When the diameter of the pipes was determined it was compared to a list of available pipes from producers and the smallest pipe diameter that fulfilled the calculated diameter was chosen

3.6.4 Pressure Drop Calculations

So that the water can be circulated in the network it is necessary to crete a certain pressure differential in the system, and that requires a certain amount of pumping power. To estimate the pressure drop in the system due to friction Frederiksen and Werner (2013) give the following equation

$$\Delta p = \frac{\lambda}{d}\frac{L}{2}\rho \mathrm{v}^2 \tag{3.7}$$

where ΔP is the pressure drop in pascals, λ is the dimensionless friction factor, d is the diameter and L is the length in meters of the pipe under consideration, and v is the flow velocity of the water in meters per second. As mentioned in chapter 3.6.3 the flow velocity for the network is assumed to be 2 m/s for this project, and thus it is only the friction factor, λ, that is unkown.

The fiction factor of a pipe is given by Colebrook's equation

$$\frac{1}{\sqrt{\lambda}} = -2\log_{10}\left(\frac{2.51}{Re\sqrt{\lambda}} + \frac{\varepsilon}{3.7}\right) \tag{3.8}$$

where Re is the Reynolds number and ε is the relative pipe roughness, both dimensionless numbers. The Reynolds number is given by

$$Re = \frac{\mathrm{v}d}{v} \tag{3.9}$$

where v is the kinematic viscosity of water in m2/s, and relative pipe roughness is

$$\varepsilon = k/d \tag{3.10}$$

where k is the absolute roughness of the pipe material in mm. For this project the value of the kinematic viscosity of water was assumed to be constant at $v = 1.519 \cdot 10^{-6}\ [m^2/s]$, which corresponds to 5°C, but the viscosity is in reality somewhat dependent on temperature (John C Crittenden et al., 2012). The district cooling pipes used in this project are stainless steel pipes with an absolute roughness $k = 0.04\ [mm]$ (Logstor, 2007; Pumpenfabrik Eduard Redlien GmbH, 2014).

Colebrook's equation is an implicit equation that is not quickly calculated and thus various different approximations have been developed. Genić et al. (2011) present a comparison of different approximations and recommend the following which was developed by Zigrang and Sylvester (1982)

$$\lambda = \left\{-2\log_{10}\left[\frac{\varepsilon}{3.7} - \frac{5.02}{Re}\log_{10}\left(\varepsilon - \frac{5.02}{Re}\log_{10}\left[\frac{\varepsilon}{3.7} + \frac{13}{Re}\right]\right)\right]\right\}^{-2} \tag{3.11}$$

The Reynolds number, relative roughness and friction factor fore each pipe diameter calculated using equations 3.9, 3.10 and 3.11 can be seen in 3.3.

Tab. 3.3.: The Reynolds number, relative roughness and friction factor for different diameters of insulated stainless steel district cooling pipes from Logstor (Logstor, 2007)

Diameter [mm]	Reynolds number, Re	Relative roughness, ε	Friction factor, λ
100	$1.32 \cdot 10^5$	0.00040	0.0189
125	$1.65 \cdot 10^5$	0.00032	0.0180
150	$1.97 \cdot 10^5$	0.00027	0.0173
200	$2.63 \cdot 10^5$	0.00020	0.0163
250	$3.29 \cdot 10^5$	0.00016	0.0156
300	$3.95 \cdot 10^5$	0.00013	0.0150
350	$4.61 \cdot 10^5$	0.00011	0.0146
400	$5.27 \cdot 10^5$	0.00010	0.0142
450	$5.92 \cdot 10^5$	0.00009	0.0139
500	$6.58 \cdot 10^5$	0.00008	0.0136
600	$7.90 \cdot 10^5$	0.00007	0.0131
700	$9.22 \cdot 10^5$	0.00006	0.0127
800	$1.05 \cdot 10^6$	0.00005	0.0124

3.6.5 Pumping Power Calculations

Based on the total pressure drop in the network it is possible to calculate how much electricity is used to drive the pumps that circulate the water. Frederiksen and Werner (2013) give the following equation for pressure that the pumps need to provide

$$\Delta p_{pump} = \Delta p_s + \Delta p_r + \Delta p_{min} \quad [Pa] \tag{3.12}$$

where Δp_s is the pressure drop in the supply pipes, Δp_r is the pressure drop in the return pipes and Δp_{min} is the pressure drop over the substation that is furthest away from the cooling plant. Δp_s and Δp_r are assumed to be the same in the case of this network and is calculated with the method described in chapter 3.6.4, while Δp_{min} is set to 50

[kPa], which Euroheat and Power (2008) present as the pressure drop over a modern substation.

When Δp_{pump} is known it is possible to calculate the required electricity for pumping with the following equation (Frederiksen and Werner, 2013)

$$P_{el} = (\Delta p_{pump}/\eta_{pump})\, V' \quad [W] \tag{3.13}$$

where η_{pump} is the total conversion efficiency of the pump and motor, which was estimated to be around 79% (Page Bloomer, n.d.; Evans et al., 1996).

3.6.6 Thermal Losses in Pipe Network

As with any thermal energy systems district cooling systems are susceptible to energy losses, which in the case of the distribution network presents itself as thermal energy gains in the pipes carrying the cooling medium. Calance (2014) estimated that the maximum thermal energy gain in a district cooling network would be below 2% of the total delivered energy in the system, and in the some system configurations the losses would be less than 1%. Given that the thermal losses are estimated to be very low they were not considered in the calculations of the piping network.

3.6.7 Chiller Plant and Storage Sizing

In order to size the system, three basic approaches were considered, as prescribed by ASHRAE (ASHRAE, 2016). The first of these system sizing approaches, full shift storage, considered sizing the storage so that the chiller plant is not operating during peak-load hours, and thus all the cooling load during peak-load hours is supply by the storage unit. The capacity of the chiller is determined by summing the total load of the peak-day, and dividing by the number of operational hours of the chiller. In that way, the chiller is sized at a bigger capacity, in order to better charge the storage unit (ASHRAE, 2016).

Alternatively, a partial shift storage approach suggests full chiller operations during peak load, but at as a fraction of peak load, thus allowing the cold storage reserve to supply the remaining load difference. The chiller capacity is thus, as reference, estimated by averaging the total daily load by the number of operation hours, in this case a 24 hour cycle. This approach allows for both lower chiller capacity and storage discharge capacity than a full-storage approach (ASHRAE, 2016). For this case, additional partial storage scenarios were creating, considering not a fraction bigger fractions of chiller output; namely 90%, 80% and 70% chiller output during peak hours. That is to say, discharge storage capacities of 10%, 20% and 30%, respectively.

For both of these approaches, the storage is sized according to the inventory left in the cold store after peak hours in a peak-design day. During the hours leading and following peak load, the cold store inventory will be depleted. The hour prior to the cooling load profile being less than the chiller output will be considered as the depleted hour, where 0 MWh of cold store discharge is available. From here, the cold storage reserve will be calculated backwards by summing the chiller output, to the cold store reserves (initially zero) and subtracting the cooling load from this operation. This will be iterated until a maximum value is obtained in the hours prior to peak load (ASHRAE, 2016).

The last approach examined a chiller plant operating without supplementary TES. That is, the chiller cooling capacity was sized to meet peak-load for the peak design day, following a 1-to-1 ratio (ASHRAE, 2016). Figure 3.3 illustrates the 3 approaches, and the supplementary partial storage cases, considered in relation to the peak-day cooling load.

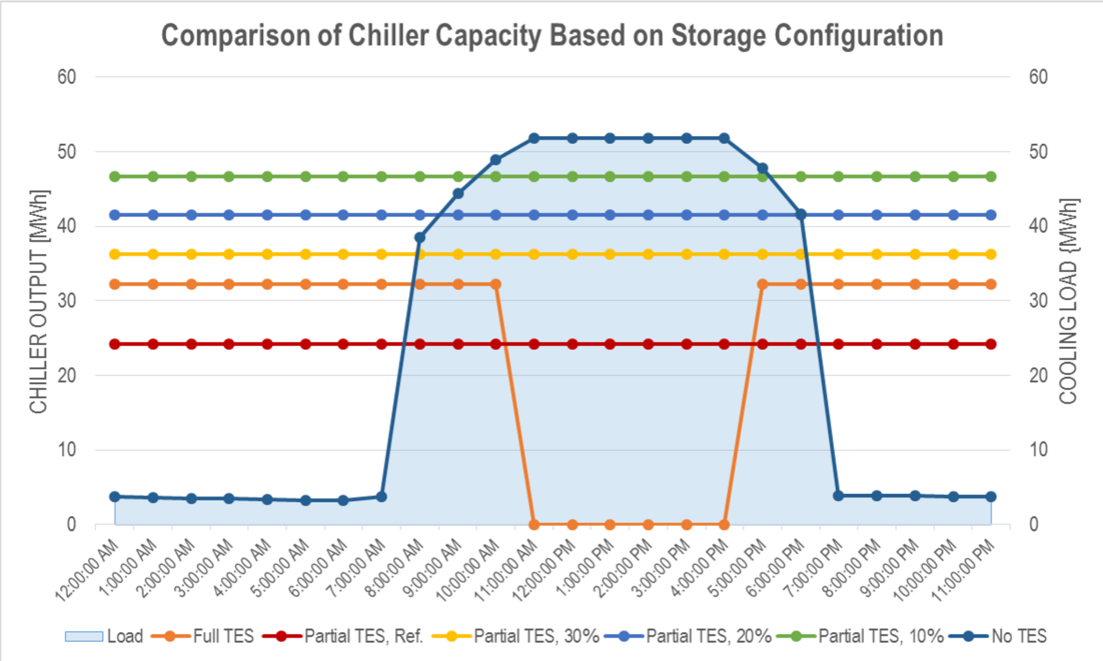

Fig. 3.3.: Capacity of chillers sized accordingly to storage discharge capacity

Finally, the storage capacities estimated were used to calculate the volumetric dimensions of the storage tank, by means of the following:

$$V_{storage} = \frac{X \cdot 3.6 \cdot 10^6}{c_p \cdot \Delta t \cdot SG \cdot \eta_{storage}} \quad [m^3] \tag{3.14}$$

, where $V_{storage}$ is the volume of the storage tank in cubic meters, X is the storage capacity, c_p is the specific heat capacity of water (4184 J/(kg·K)), $Deltat$ the temperature differential in the layers of the storage tank, SG the specific gravity of water (998 kg/m^3), and $eta_{storage}$ the efficiency of the storage.

3.7 Economic Costs

3.7.1 Distribution Network Costs

Costs for the construction of the distribution network were taken form Peruvian sources when available, or sources from neighboring countries. Labour and supervision costs for installing water pipes came from those used by the Peruvian public water utility, as stipulated by the Superintendencia Nacional De Servicios de Saneamiento (SUNASS, 2015). Since it was not possible to find sources regarding prices for insulated district cooling pipes in Peru, that data came from a recent district cooling project in Medellín, Colombia (Restrepo, 2011). Using the aforementioned information, and information from pipe supplier regarding available pipe diameters (Logstor, 2007), the total investment costs per meter of pipe as a function of pipe diameter was extrapolated and can be seen in figure 3.5. It should be noted that the graph shows the investment costs per meter of two pipes laid side by side, since in the network it is always necessary to lay one pipe for supply and another pipe for return. Operation and maintenance costs were estimated to be 0.5% for the distribution network based on data from IEA (2002b). The cost breakdown between procurement and installation costs for different diameters of pipes can be seen in figure 3.4. As can be seen from the figure the procurement costs start to dominate the the total cost as the pipe diameter grows.

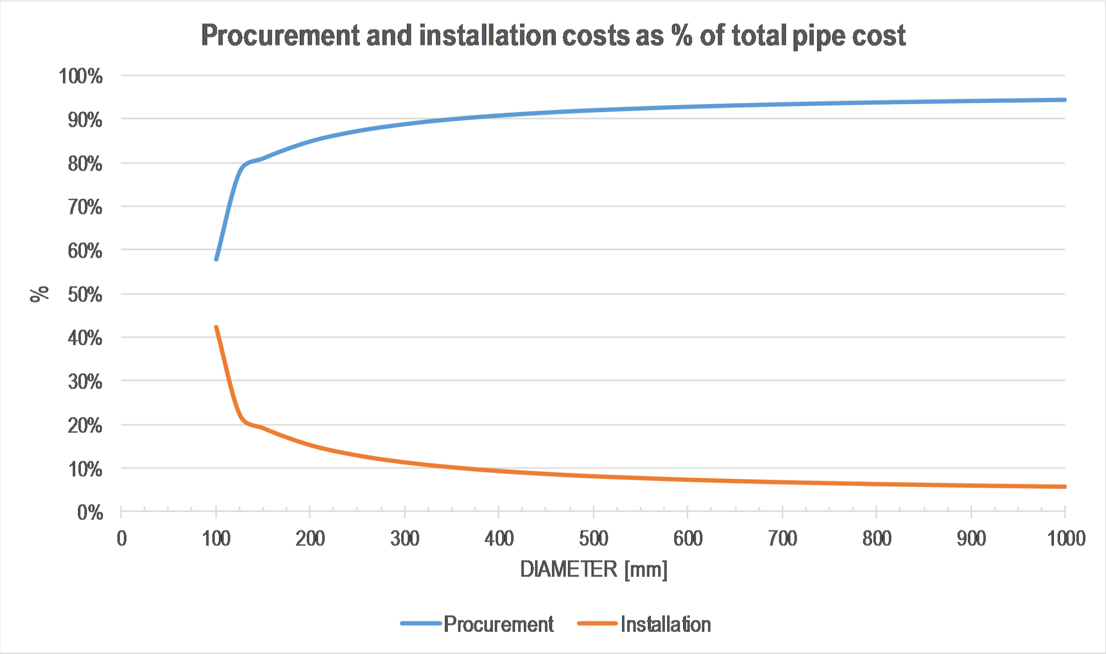

Fig. 3.4.: Division of total pipe costs as a function of pipe diameter

According to European Standard EN253:2009 the minimum thermal lifetime of of district heating pipes should be over 50 years for systems operating at a temperature below 115°C (CEN, 2009), while other sources give the lifetime of district heating networks at between 40 and 50 years (Energistyrelsen, 2015). Since district cooling networks operate at considerably lower temperatures than district heating networks it is assumed that the lifetime of those networks would not be shorter than that of district heating networks. The lifetime of the distribution network is thus assumed to be 50 years in this project.

Something about the long lifetime of DC pipes

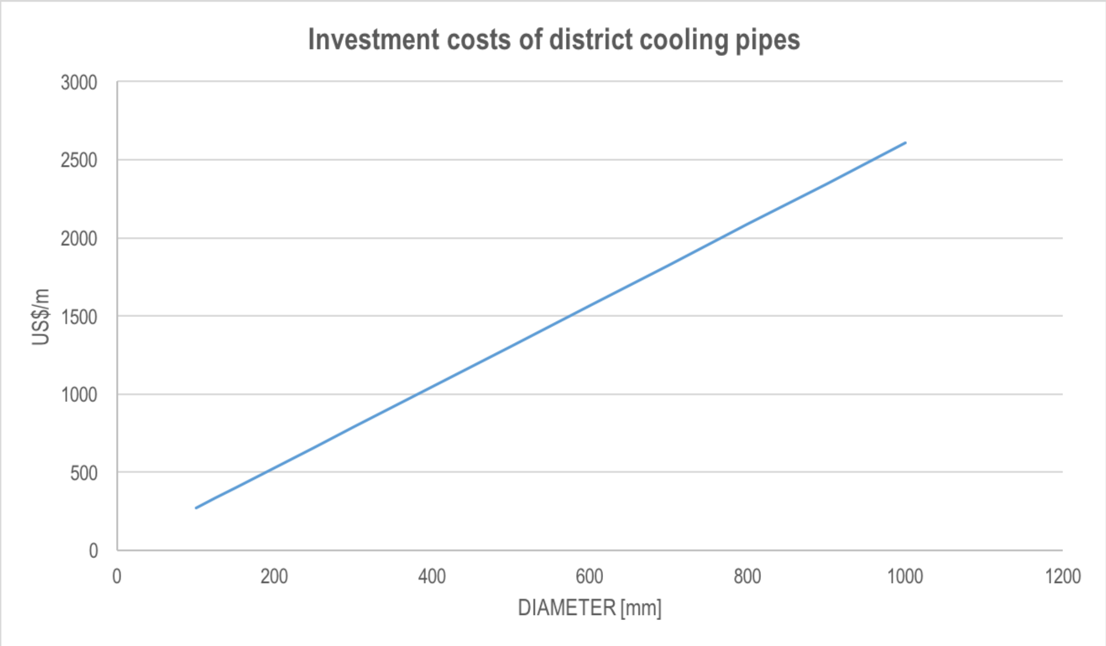

Fig. 3.5.: Extrapolation of insulated district cooling pipe costs per meter of two pipes

3.7.2 Circulation Pumps

The process of determining the price of the circulation pumps used in the project was similar to the process used for determining prices for district cooling pipes. Prices of pumps was found in the literature and used to extrapolate the price for pumps used in this project. Figure 3.6 shows the price graph for the circulation pumps extrapolated by using data from Alkan et al. (2013). The fixed operations and maintenance cost of the pumps was estimated to be 3% based on data from IEA (2002b) and the lifetime was estimated to be 20 years.

3.7.3 Cooling Plant Capacities and Costs

Taking the chiller plant sizing estimates, explained in Section 3.6.7, the following values from ASHRAE's database were used in order to get typical installation costs, which were then assumed as capital investment. Likewise, maintenance costs for the chillers were also gathered from ASHRAE (2016):

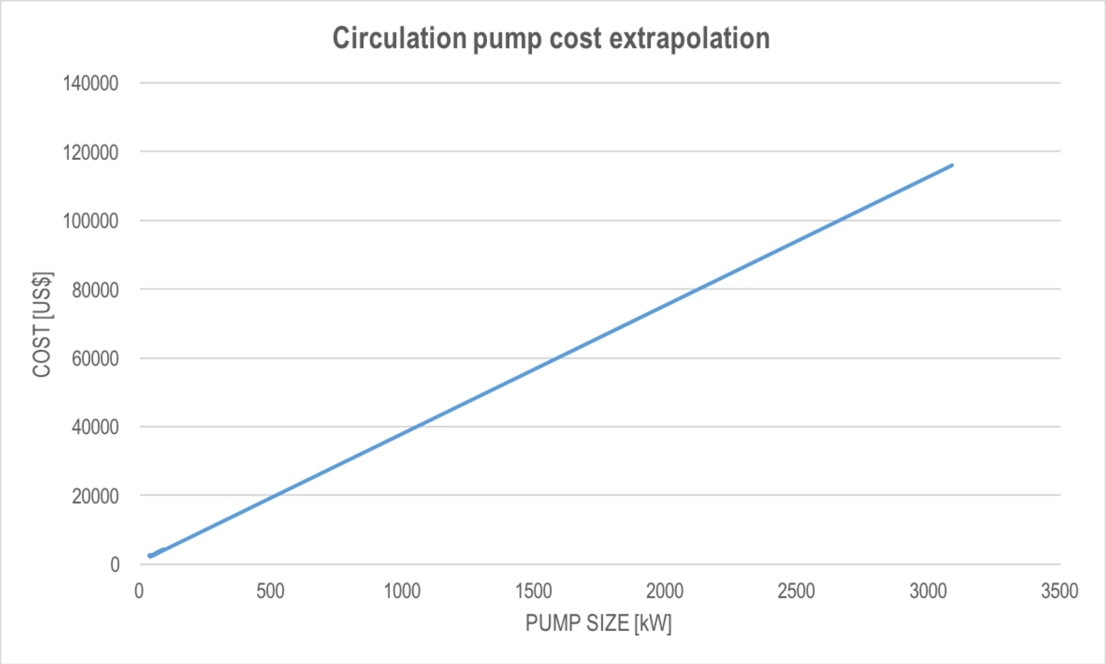

Fig. 3.6.: Extrapolation of pump costs per kW

Tab. 3.4.: Typical mid-value chiller costs from ASHRAE's database (ASHRAE, 2016)

Chiller Type	Install Cost [USD/kWh]	Maintenance [USD/yr.]
Electric (Vapor Compression)	99.5	4,350
Absorption	341.5	5,150

Additional price data of the district cooling plant components was also collected from COWI (2016) and Phetteplace et al. (2013), corresponding to cooling tower prices by installed capacity, storage price by volume, and overall plant components including auxiliaries, electronics and building costs by install capacity. These costs are presented in Table 3.5

Tab. 3.5.: Costs of additional plant Components

Component	Install Cost	Source
Chilled water storage	290.11 USD/m^3	(COWI, 2016)
Cooling tower	193.4 USD/kW	(COWI, 2016)
Auxiliaries & electric comps.	432.8 USD/kW	Derived from (Phetteplace et al., 2013)

In order to estimate energy and water usage, and their related costs as operational expenses, the following data was used:

Energy and water consumption data was obtained from IEA (2002a). The electricity usage from the electric equipment and auxiliaries was estimated as a function of installed capacity, using the factor presented in Table 3.6. Likewise, water demand was estimated based on the installed chiller capacity.

Tab. 3.6.: Typical chiller plant characteristics. Average COP values from (ASHRAE, 2016), and electricity and water capacity and consumptions from (IEA, 2002a)

	Electric Chiller	Absorption Chiller
$COP_{typical}$	4.7	0.85
El. comps & auxiliaries capacity [$kW_e/kWh_{chiller}$]	0.28	0.06
Electric demand [$kW_e/kWh_{chiller}$]	0.35	0.15
Water demand [$m^3/kWh_{chiller}$]	2.7	5.5

The coefficient of performance (COP), defined in Equation 3.15, was used to determine the require energy input for the chillers in order to meet an output equal to the cooling load, thus, effectively working as an efficiency factor for the pumps (ASHRAE, 2016).

$$\text{Energy Input} = \frac{\text{Energy Output}}{\text{COP}} \tag{3.15}$$

The COP values for the chillers were gathered from ASHRAE's District Cooling Guide and Handbook of HVAC Systems and Equipment (Phetteplace et al., 2013; ASHRAE, 2016). These documents were selected since they present a comprehensive and unified range of typical efficiency values for chiller equipment gathered by ASHRAE. The specific COP values selected were taken from the lower range of values presented for each type of chiller, in order to account for system inefficiencies. As Phetteplace et al. (2013) elaborates, the COP is a function of temperatures, and in the case of space cooling this will be dictated mostly by outdoor temperatures and indoor comfort; thus, the COP changes throughout the year with the corresponding temperature variations. In the particular case of the project, the corresponding variations in COPs are assumed to average out into the selected lower range values.

3.7.4 Energy and Water Pices

Based on the required energy and water inputs, the total cost of consumption was estimated according to the local Peruvian prices. An electricity price of 56.76 USD/MWh was considered as per OSINERGMIN (2016b). Likewise, a gas price of 19.03 USD/MWh was considered as derived from the volumetric gas price and its caloric value OSINERGMIN (2015b). Water prices were gathered from the local water utility, SEDAPAL (2017), and included water supply and sewage prices corresponding to 1.58 USD/m^3 and 0.66 USD/m^3, respectively.

3.7.5 Salvage Value

Given that the components in the system have different technical lifetimes and different start times along the prospective project implementation, the use of product depreciation along project lifetime for each of the components allows for a fair accounting of capital costs. For the case of HVAC systems, a salvage value amounting to a 5% of the original value of the component at the end of its lifetime has been reported in similar applications (Krus, 2004; Murugavel and Saravanan, 2010), along with the use of a fix annual depreciation value by means of the straight-line method (Haberl, 1993).

The lifetime of the main plant components considered in the costing calculations was gathered from ASHRAE's database (ASHRAE, 2013b). Average technical lifetimes of the storage and the piping network were obtained from IRENA (Zhou et al., 2013) and CEN (2009), respectively. The lifetime data is listed in Table 3.7.

Tab. 3.7.: Lifetime of the different components in the district cooling system.

Component	Lifetime [years]
Chillers	23
Cooling tower	20
Storage	20
Auxiliaries & Electric comps.	20
Piping	50
Pumps	20

3.8 Economic Indicators

The project has different annual cash flows throughout its lifetime, coming from recurring operational expenditures, from specific capital investments, or revenue streams from cold supply sales and salvage value of the equipment at the end of the project lifetime. In order to account for the different value of money in time, the net present value (NPV) was used in the cashflow calculations. The NPV allows for this comparison between cashflow components in different periods by discounting the value of money along the different years considered in the project and bringing those values back to the starting year (Frederiksen and Werner, 2013). The NPV can be expressed as follows:

$$NPV = C_0 + \sum_{n=1}^{T} \frac{C_n}{(1+i)^n} \tag{3.16}$$

, where C_0 represents the initial capital expenditures at year zero, C_n the cashflow during a subsequent year, i the discount rate, and n the corresponding year during the project.

For the discounted cashflow calculations, a 4% discount rate was assumed as per the suggested rate dictated by Peru's Central Reserve Bank (BCRP, 2017). However, suggested discount rates for project valuations vary in the Peruvian context (MEF, 2015). Thus, variations in these assumption were furthered examined through a sensitivity analysis, as described in Section 3.9.

Based on this calculations, different net present values were estimated to evaluate the overall costs of the system over a 20 year project lifetime. It must be noted that the term net present cost (NPC) will be also used through the presentation of the results. The net present cost is taken at face value as the inverse of the net present value. In other words, a positive NPC denotes outgoing money like capital and operating expenditures. The higher the value of NPC, the more costly the project valuation is, and vice-versa.

In addition to the above, the levelized cost of energy was also considered as a way to account for the generated energy output in the form of cooling. The levelized cost of energy is the ratio of total lifetime costs of the system and the total energy output generated, thus accounting for the cost of producing one unit of energy, and yielding the minimum energy cost needed for the system to break even (Short et al., 1995). This parameter is defined as shown in Equation 3.17.

$$\text{Levelized Cost} = \frac{\text{Lifetime costs of the project}}{\text{Energy output}} \tag{3.17}$$

The levelized cost of energy allows for the comparison of different technologies with different scales of implementation, and is used as a common reference parameter to compare energy generation technologies (Short et al., 1995; Bruckner et al., 2011); although, its application extends also to district energy projects (Bratanova et al., 2015; Gudmundsson et al., 2013; Fredslund et al., 2016). Throughout the report, this parameter is referred to as the levelized cost of cooling (LCOC).

3.8.1 Consumer Scenario Analysis

Two comparison scenarios were considered for the analysis presented in Section 7.2: a business as usual scenario (BAU), and a district cooling connection scenario. This was assumed in order to gage the extend in which the technologies might differ — cost-wise — from a consumer perspective. This perspective considered the total bulk of potential consumers identified for the sites of the district cooling implementation.

The BAU scenario was build on the basis of the consumers developing on-site cooling solutions, and thus, used the same economic calculations with an initial investment on chiller and equipments, and recurring annual operation and maintenance expenditures.

The estimation of the capital investment costs for the cooling technology, had as basis the system sized according to a "No Storage" approach, as presented in Section 3.6.7. In addition, it considered the same range of COP values for an electric chiller, and its corresponding price based on installed capacity. Subsequently, the O&M costs were calculated taking the total annual cooling load for the total consumer bulk, starting from year 1 in the cash flow calculations.

For the case of the district cooling connection scenario, the capital investments and O&M costs of the BAU scenario were taken as expected net present cost savings. An additional cost component, corresponding to the purchase of cold from the district cooling supply was included as a cashflow expense. The initial price considered as district cooling sale price was assumed to be LCOC of the systems, as this would be the minimum sales rate by which a district cooling provider would break even.

The difference in net present costs between these two alternatives was then contrasted, an considered as the total expected consumer savings.

3.9 Sensitivity Analysis

The sensitivity analysis pivoted around two main sensitivities: the impact of the cooling sale price in the consumer scenarios, and the impact that the general cost assumptions might have on the economics of the district cooling project.

For the former, the estimation of cooling price followed an iterative approach. In other words, the cooling sale price was iterated until both the net present costs of the BAU and District cooling connection scenario were the same. This was then set as a price cap, since it would be a cost threshold for consumers to connect to the system. This sale price was then used as an input parameter for calculating a revenue component in the cashflow calculations for the district cooling system implementation by itself. In this way, the maximum allowable price for the system was estimated, along with its corresponding net present costs and expected payback time.

In the case of the general implementation assumptions, the sensitivity analysis consisted of varying key cost parameters. Each cost parameter was varied independently of each other in order to determine its specific effects on the total net present cost of the systems. The variations in these parameters were then ranked in order of impact, and were presented in Tornado Charts for ease of visualization, as seen in Section 7.3.2.

Governance Framework

4

In this chapter, the existing policies related to energy efficiency, sustainable construction, and local regulation are presented within the context of the Peruvian legal framework and institutional setting; expanding upon what was introduced in Section 2.4. Examining these will serve as a foundation from which to further conduct analysis about the specific barriers of district cooling and about favorable conditions found in the Peruvian governance structures that can, respectively, hinder or foster this type of implementation. This in turn, will serve for the purpose of answering the following research question:

1. What current policies and institutions could foster, or hinder, the development of district cooling in Lima?

4.1 Current Policies and Legal Framework

Peru's current framework conditions are bounded by established laws and regulations. As identified in Section 2.4, a number of public policies and initiatives related to energy efficiency, energy resilience, decarbonization, pollution, and climate change can be relevant to the general case of district cooling. Specifically for the Peruvian context though, two major laws can be found as the basis from which these can be further constituted. These are: the Law on the Promotion of Efficient Energy Use (MINEM, 2000), and the General Environmental Law (MINAM, 2009). Along with these laws, a set of related regulation codes and strategies decreed by the government further comprise the relevant normative structures under which a district cooling development in Peru would function. These are outlined in the following sections.

4.1.1 Environmental Framework

The General Environmental Law (Law N° 28611, 2005) sets the policy grounds for matters related to environmental considerations in Peru. Through this law, the Peruvian government sets as its main environmental policy objectives the prevention and control of environmental pollution — mainly from emission sources —, and the sustainable development of the country's resources, areas, and population. The development and rollout of public policies throughout the different levels of Government are bound with these and other environmental policy considerations stipulated in the General Environmental Law (MINAM, 2009).

The Ministry of Environment (MINAM) serves as the main government entity tasked with carrying through the aforementioned objectives. In addition, MINAM also serves as a coordination platform with other ministries and institutions on matters intrinsically but not directly related to national environmental policy considerations (MINAM, 2009).

In line with the above, the National Strategy Against Climate Change set forth by MINAM (Decree Nº 011-2015-MINAM, 2015) serves as the main tool for managing efforts against climate change in Peru (MINAM, 2015a), linking these efforts to international agreements, namely the United Nations Framework Convention on Climate Change (MINAM, 2016). In general terms, this strategy has as main goals to (MINAM, 2015c):

- Increase the awareness and adaptive capacities of the population, economic actors and the Government, for facing the adverse effects and arising opportunities of climate change
- Reduce GHG emissions through the participation of Government and society.

In accordance with these goals, MINAM, in tandem with other government institutions participate in the proposal of Nationally Appropriate Mitigation Actions (NAMAs) on different fronts, as part of Peru's commitment to reduce GHG emissions. These actions are led by other relevant ministries according to their core competences, while MINAM serves as a coordination platform, as previously stated (MINAM, 2015b). Examples of this are, for instance, the development of Energy Efficiency and the Sustainable Housing and Construction NAMAs, led by the Ministry of Energy and the Ministry of Housing, Construction and Sanitation, respectively.

4.1.2 Energy Efficiency Framework

The Law on the Promotion of Efficient Energy Use (Law N° 27345, 2000) lays down the policy framework foundations for energy efficiency in Peru. Through Article 2, this law assigns competencies over to the Ministry of Energy and Mines (MINEM) for the promotion, oversight, planning and execution of national plans and programs related to the above. Moreover, it ascribes MINEM with developing appropriate energy efficiency policy initiatives in coordination with other public and private institutions (MINEM, 2000).

Stemming from this, the pertinent regulatory code on the promotion of efficient energy use (Decree N° 053-2007-EM, 2007) further expands on the general dispositions of the aforementioned law. More specifically, it defines the following actions — among others — to be conducted at an institutional level by MINEM (MINEM, 2007):

- conduct educational training and promotion at all levels of government and society on the topic of energy efficiency
- develop government programs to foster energy efficiency by sectoral use
- promote access to financing mechanisms for energy efficiency programs
- set reference energy usage indicators by sectors
- promote the phase out of low energy efficient appliances and technologies
- establish minimum energy efficiency requirements for technologies according to their use in productive activities
- coordinate with the Ministry of Housing, Construction and Sanitation (MVCS) the inclusion of energy efficiency criteria in construction regulations

In addition to the above, MINEM sets forth the main NAMAs geared towards the Peruvian energy sector, including national actions related to energy efficiency (MINAM, 2016).

4.1.3 Sustainable Construction Framework

As mentioned in Section 2.4, sustainable construction plays a key role alongside other energy related initiatives when it comes to the development of district energy projects. Parallel to this parting premise, the existing framework conditions mentioned in Sections 4.1.1 and 4.1.2 outline a relationship between the construction sector and both climate change and energy efficiency policy measures.

The inclusion of energy efficiency at a construction level takes as foundation the existing National Building Regulation set forth by the Ministry of Housing, Construction and Sanitation (MVCS), namely through the Energy Efficient Thermal and Lighting Comfort Technical Norm (Technical Norm EM.110, 2014). This norm — the first of its kind in Peru which includes energy efficiency parameters at a construction level — defines minimum standards for lightning and for building envelopes, which must be met by new constructions and existing building stock undergoing refurbishments (MVCS, 2014).

Building up from this technical norm, the Sustainable Construction Technical Code — mentioned in Section 2.4 — considers additional energy efficiency measures such as the installation of energy efficient lightning and the use of energy efficient refrigeration and cooling appliances, as well as the installation of solar heaters for selected building types. The main objective of these, as stipulated by Decree N° 015-2015-VIVIENDA (2015), is to promote new ways of developing constructions and cities, given the current climate change context and the need for rational use of natural resources and reducing GHG emissions. The area of application of these measures, however, is not yet obligatory but rather optional for both new and existing constructions (MVCS, 2015b).

4.1.4 Municipal Regulation

The Municipality of San Isidro (MSI), serves as the main local governing body of the district. In this regard, it is in charge of the local zoning and specific building permitting as per its municipal functions (Ordinance N° 1067-MSI, 2007; Ordinance N° 1328-MSI, 2009). The specific zoning, for instance, may restrict certain types of constructions being build in the areas of the district, according to their end-use and function (MSI, 2007; MSI, 2009).

4.1.5 Legal Framework Summary

As seen, a number of policies and legal considerations have been touched on, which may be related to district cooling. A summary of these is presented in Table 4.1.

Tab. 4.1.: Regulatory statutes related to energy efficiency and sustainable construction.

Law / Regulatory Decree	Relevant Institution
General Environmental Law	Ministry of Environment
National Strategy against Climate Change	Ministry of Environment
Law on the Promotion of Efficient Energy Use	Ministry of Energy and Mines
Regulation for the Promotion of Efficient Energy Use	Ministry of Energy and Mines
Technical Norm for Thermal and Light Comfort with Energy Efficiency	Ministry of Housing, Construction and Sanitation
Sustainable Construction Technical Code	Ministry of Housing, Construction and Sanitation
District Urban Zoning	Municipality of San Isidro

4.2 Institutional Stances and Dynamics

The existing legal framework, discussed in the previous sections, pieces together policy components related to different areas of competency. This policy overlap is clearly embodied by a number of institutions, which include elements of both energy and environmental policy alongside with construction related regulation through their participatory involvement in the policy making-process.

For the case of district cooling, the conjunction of the actors must be evaluated in tandem, in order to determine how their underlying dynamics may end up influencing energy efficiency developments, and more specifically, influencing a localized district energy implementation. Hence, these must be understood under the governance context of Peru, and in relation to specific topic areas that may affect or involve them in a district cooling case. The following sections outline some of these dynamics and stances, gathered from interviews with local actors, which could be tied to opportunities and barriers to be faced by a district cooling implementation.

4.2.1 Initiatives and Opportunities

A key element that serves as starting point, is having an outlook of the undergoing initiatives, and their effectiveness. This will facilitate the process of finding new windows of opportunities for an initiative such as district cooling to take form.

In this regard, the general context seems to have favorable elements. Different institutions, both in the public and private sector, are either promoting or adopting new approaches, which tend to move in the same general direction towards sustainability and greater energy efficiency.

> *"There is no prime office building being built right now that does not have at least one sustainable attribute or a certification, either LEED or EDGE." (PeruGBC, Personal Communication, 2017)*

> *"Progressively, everyone is moving towards individual sustainable building approaches and these initiatives coalesce." (MVCS Specialist, Personal Communication, 2017)*

> *"The municipality is aiming at making the district a sustainable district, ...specially now under the context of the Paris Agreements"" (Municipal Officer, Personal Communication, 2017)*

> *"We have energy efficiency labeling regulation that is being passed now, and that includes air conditioners. Basically for public institutions..."" (MINEM Specialist, Personal Communication, 2017)*

“There are a lot of initiatives right now to try to improve the electricity distribution network so that the frequency and duration of interruptions decrease."" *(MINEM Specialist, Personal Communication, 2017)*

Many factors are at work behind this trend. The benefits of energy efficiency and sustainability are becoming apparent; giving rise to the interest for new solutions. The driving forces behind new initiatives include general economic considerations related to profit gain or the expected savings on, for instance, utility services. Likewise, general considerations about energy reliance and the environment also play a role in the formulation of new alternatives.

“Real estate developers are seeing the economic benefit through their projects. They are renting their building spaces a bit more expensive than regular buildings, because of what they offer to their tenants ...they offer lower water and energy bills at the end of the month and they offer a better quality of air, so it is going to be translated into more productive employees and a better space for them to work, they want to stay there, work more, in the end it is money for them."" *(PeruGBC, Personal Communication, 2017)*

“In the distribution network, ...it is the distribution company that needs to supply the energy during the peak hours, so it is in their interest to reduce consumption during those hours so that they don’t have to purchase a higher cost energy."" *(MINEM Specialist, Personal Communication, 2017)*

“There are a couple of issues to consider that need to be properly weighted. One is emissions, of course,...and air quality."" *(MINAM Specialist, Personal Communication, 2017)*

Arguably, the current context presents key opportunity areas for a district cooling implementation based on the existing drivers mentioned above. A solution such as a district cooling system has the potential to tackle energy savings and energy efficiency, by both reducing the energy consumption costs and by shifting load away from peak-hours (Phetteplace et al., 2013). Moreover, by reducing the amount of refrigerant use that would otherwise be used by conventional cooling equipment (UNEP, 2015), it positively addresses environmental concerns.

However, the extent of this opportunity areas may be somewhat limited. As mentioned by local stakeholders, the existing initiatives are somewhat new. This means, that the benefits of this solution may not be readily apparent or its benefits taken at face value, as they are not deep rooted in the institutional decision making process.

“Up until approximately 4 years ago, the focus on sustainable construction, sustainable cities or even sustainability in general was fairly new."" (MINAM Specialist, Personal Communication, 2017)

“Even some tenants of sustainable buildings don’t really know where they are, what the benefits are for them."" (PeruGBC, Personal Communication, 2017)

Despite this yet "green" state, change has been enacted. Logically, the framework provided by public policy, as described in Section 4.1, has served by facilitating promotion tools for some new initiatives to be considered and by engaging different actors, like is the case with the different government entities and real state developers. The platform provided by policy and institutional initiatives, in turn, may be required for a district cooling system to take place and, in that manner, make its potential benefits be known.

4.2.2 Institutional Barriers

Governmental institutions acknowledge the positive effects of involving different actors, both from other government entities and civil society, in the decision and policy-making process. As documented by Mcnulty (2013), Peru’s participatory institutions fall under a corporate design in which corporate and civil society organizations are involved.

Although able to accomplish change, shortcomings in the existing governance structures do exist, and may curb potential district cooling developments. On this front, the stakeholders involved in the policy and decision making process are able to provide insights on the effectiveness of their dynamics under the current local context.

“Fights and competition over competencies ...is common still in our culture. You can have funding, technology, everything but if the institutions don’t work then there is no way to move forward"" (MINAM Specialist, Personal Communication, 2017)

“If you talk to people who are more related to the electricity sector they are saying, ’we have an over-offer of 55% to demand, why do we want to promote energy efficiency?’ There is sometimes kind of conflicting attitudes on the issue.” (MINEM Specialist, Personal Communication, 2017)

“As a local government we have limited intervention because of the laws. Within the scope of what we can do, we are working on some regulations. ... The autonomy of the municipalities is in some ways beneficial for internal purposes, but hinders interconnectivity with other districts even though there are some general

> *guidelines about collaboration" (Municipal Officer, Personal Communication, 2017)*

The lack of collaboration, and potential differences in stances within the institutions may thus be a big obstacle when it comes to creating new policy tools for favoring new implementations, or simply creating a setting in which new initiatives could thrive. These hurdles may apply to any new energy efficiency initiatives, such as district cooling, since they are subject to different priorities even within a single competent institution. In addition, potential expansions of a district energy project, could be hindered by institutional segmentation. For instance, this may be the case under a scenario with distinct policies and regulations from one local government to another in which such a project takes place.

Moreover, the general outlook for setting up mechanisms of promotion will be limited by institutional approaches. For instance, incentives or direct control over consumer options may not be viable due to existing policy. In a similar case, top-down approaches may also limit the availability of such mechanisms.

> *"The government can't control the private sector. ...it does not want to force anyone to purchase anything ...or favor certain technologies or models or companies over others. ...the only area which we actually have any control is in the public sector. Incentives, also. ...Basically, all we are allowed to do is to create funds that are independently financed or create informational campaigns which tell people, 'this is in your interest because it ends up being cheaper for you'." (MINEM Specialist, Personal Communication, 2017)*

> *"We are definitely collaborating with local governments, for example ...to implement their own distributed generation system and they can't because they are waiting on the national regulation to pass. ...but in the end, it does need to come from the top down in terms of actually permitting these things to happen. ...Then, also there is the interest at the federal level that may not necessarily apply at the regional level, so it would be nice if the regional governments had a little bit more control and could operate autonomously, but this is not the case. " (MINEM Specialist, Personal Communication, 2017)*

Given the lack of incentives, the main driver of change for some institutions ends up being the actual cost-benefit that an alternative, like district cooling, may bring. This, naturally applies to the potential mass of consumers just as well, as it does for the economics of the implementation itself.

> *"Out of the cost-benefits, the most important item is the economic aspect/benefits. These cost-benefit analyses are complex for cities and urban solutions, ...A project can be environmentally friendly, awesome, good for energy saving, but if it is too expensive it can't be developed." (MVCS Specialist, Personal Communication, 2017)*

> *"For building/business owners the bottom line is often their biggest consideration when evaluating projects. In these cases it is important that the business case and benefits of switching to district cooling are shown.." (UNEP, Personal Communication, 2017)*

In addition to the economic interest of private organizations, society at large will have a take on how an implementation like district cooling will unfold, since they too are affected by these changes. The impact that a district cooling initiative might bring them, might not necessarily be a favorable one. This might specially be the case in an area as dense and trafficked as the San Isidro district. Ultimately, the general discontent that the project implementation might greatly hinder the project.

> *"A few months ago we had some debates, complains and — you know — chaos, because of works done on some roads. They had to be broken for constructions for the water network, and then someone else came for maintenance, and again it was broken for electricity, and then for the gas network, and there are no proper integrated regulations for some of the piping networks laid below the roads, so that's also a major issue. We need to consider those things so that we can avoid critique when making new regulations and implementations. When people start complaining about this things, the projects often begin to fail. That's also why we start with little things, because if we start asking too much and getting too sophisticated, then the implementation gets overly complicated with other things that are not on the same level, and then the project fails. That's also sometimes why sustainability has a hard time selling." (MVCS Specialist, Personal Communication, 2017)*

Thus, overcoming these barriers becomes critical for the district cooling implementation. Given the current challenges, the success of the implementation will pivot around how different priorities are aligned, in connection to district cooling, at an institutional level. The economic costs-benefits, will too, play a key role in show casing the merits in favor of district cooling as a new initiative. The competent institutions may in one way or another, despite their limitations, help promote the benefits of a district cooling project and forewarn societal actors of the impacts it may have.

4.3 General Outlook and Considerations

The policies present in Section 4.1 and the perspective provided by Section 4.2.1, expose existing opportunity areas for district cooling to work around the barriers presented in Section 4.2.2. Namely, the existing environmental, energy efficiency and sustainable construction frameworks serve as platforms that bridge together the specific interests held by a number of institutions.

District cooling relates to these platforms in different ways, be it by reducing pollutant emissions or increasing energy efficiency both at a building or country level. The connection that these institutional platforms provide with civil society, serves as a promotion mechanisms by which the benefits of district cooling can become widespread. For instance, given the government's limitations to impose initiatives in the private sector, a district cooling implementation may start by tackling public buildings with special zoning easement from local authorities. In this way, the institutions themselves pose as the "proof of concept" needed for other actors to assess the success or failure of district cooling and its benefits.

5 Cooling Situation in San Isidro

This chapter presents an analysis of the cooling situation in the San Isidro district in Lima. The cooling degree days for Lima are presented along with a map of the estimated current installed cooling capacity in the district, which is considered a proxy for peak cooling demand. This results, serve as the foundation for all subsequent calculations in upcoming chapters, and provide an answer to the following research question:

2. What is the current cooling situation in the commercial zone of the San Isidro district in Lima?

5.1 Cooling Degree-Days

Using Equation 3.2, the cooling degree-days were calculated for Lima for the reference year of 2016 and are shown in Figure 5.1. The total annual cooling degree-days calculated using this method were 1048 days. The cooling degree-days were used to see how Lima compared to other cities that currently have district cooling in order to do a preliminary investigation into the feasibility of building a district cooling network in San Isidro. Table 5.1 shows a comparison of the cooling degree days in Lima with the cities of Barcelona and Medellín, both of which have a running district cooling system. With Barcelona having 543 cooling degree days and Medellín having 476 cooling degree days it is possible to assume that there is some potential for a district cooling system in Lima.

Tab. 5.1.: Cooling degree days for the cities of Lima, Barcelona and Medellín.

	Lima	Barcelona	Medellín
CDD [°C]	1048	543	476

5.2 Cooling Capacity Mapping

A mapping of the cooling capacity in the target areas within San Isidro was conducted in order to understand where the main demand would be located, in the case a district cooling system would be built. The results of the cooling capacity mapping can be seen in figure 5.2. The map shows that there are three noticeable hotspots within the area that was examined in San Isidro district. The hotspot that lays to the west is situated in

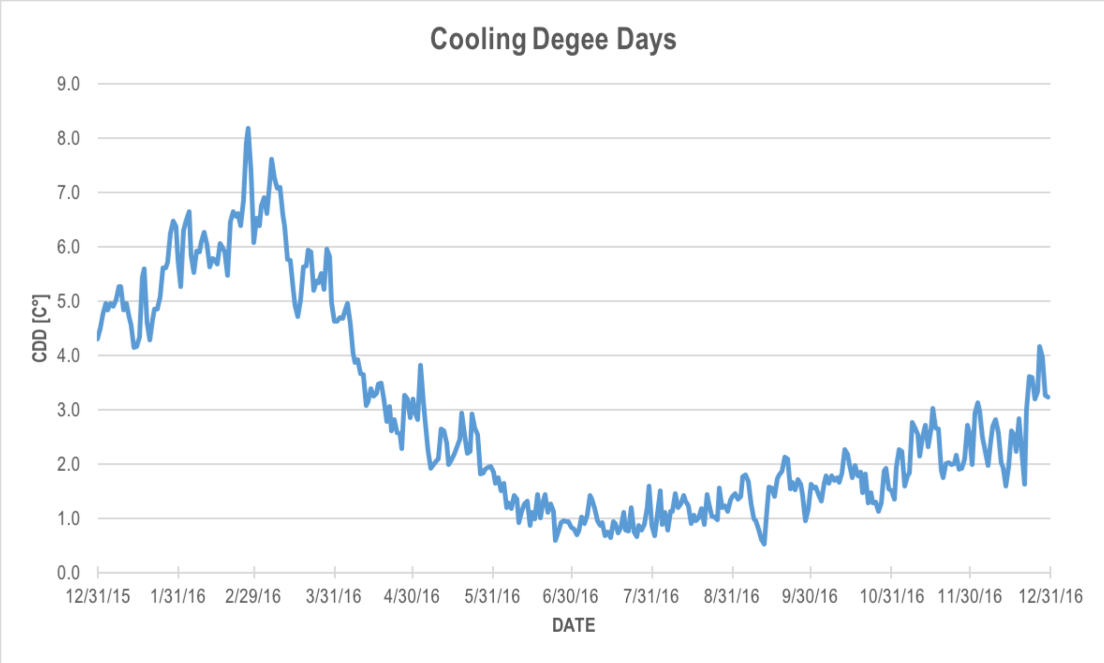

Fig. 5.1.: Cooling degree days in Lima for the year 2016 with a base temperature of 18.3°C

a Special Regulatory zone (Zone del Reglamentación Especial) while the two easterly hotspots are located within the Metropolitan Commercial Zone (Zone del Comercio Metropolitano). Based on this map it was decided to focus the development of the district cooling system around these hotspots.

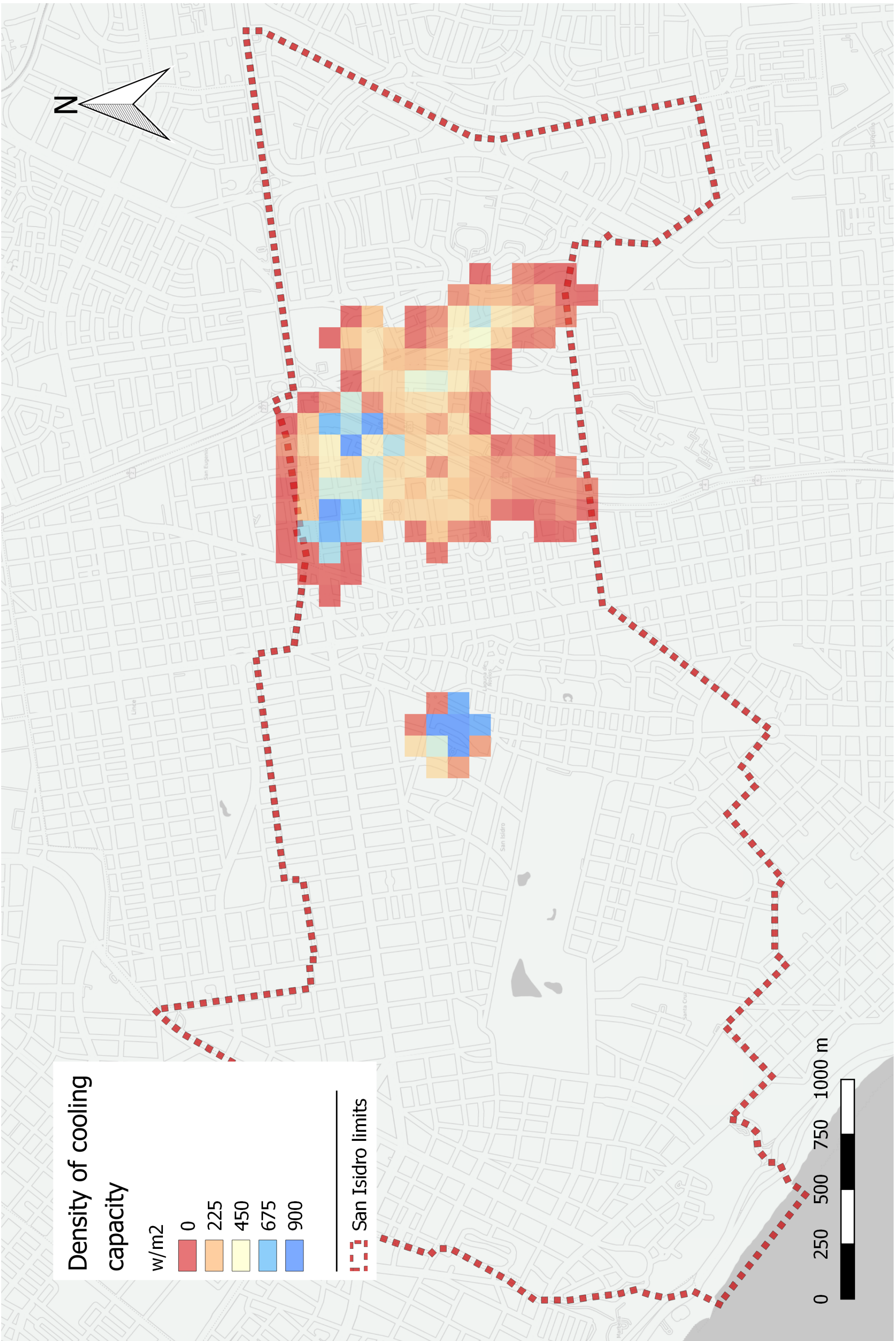

Fig. 5.2.: Estimated cooling capacity density in San Isidro based on floor area and cooling energy usage per square meter. Each square on the map is 100 meters per side, covering 10,000 m2

System Sizing and Costs

6

This chapter focuses on the general design aspects of the district cooling system. First, plant sites will be identified. Then, the design, development approach and cost estimates of the distribution network will be discussed. Following this, several plant options feeding the distribution network will be assessed by sizing the configuration of chiller plants in tandem with thermal energy storage. Finally, cost estimates for the complete system will be presented. As a result, this chapter will facilitate answering the following research question:

3. How should a new district cooling system be designed?

6.1 Plant Site Selection

San Isidro is a heavily developed urban district and, as such, has a limited amount of free space available for new constructions. After reviewing the areas close to the cooling hotspots, only a few select places were identified as potential locations for district cooling plants. Figure 6.1 shows the potential site locations for district cooling plants, one (marked "1" on the map) in the special regulation zone in the west and two (marked "2" and "3") in the metropolitan commercial zone in the east.

Locations 1 and 2 are in small areas that serve as parks, while location 3 is part of the road intersection between Avenida Javier Prado Este and Av. Paseo de la República. In the case of the Special Regulation Zone, there is simply a complete lack of suitable locations for the placement of a cooling plant except for the area around the suggested location, 1. On the map presented, there seems to be another area approximately 150 meters north of the selected spot, but further investigations revealed that this area is actually a construction site. With regards to the Metropolitan Commercial Zone, there were two locations considered as candidates. Location 3 is close to the main cooling hotspots, but at the edge of the district, and far away from the rest of the buildings that would be connected to the district cooling system. Location 3 also suffers from the fact that although it has plenty of space, it is situated in the middle of an intersection, and that might make that location unsuitable. Location 2 is, on the other hand, further away from the main cooling hotspots, but it is situated close to the area that will be considered as the first phase of the project, and relatively central compared to buildings in the CMZ. It was thus decided to base a plant for the CMZ are at location 2.

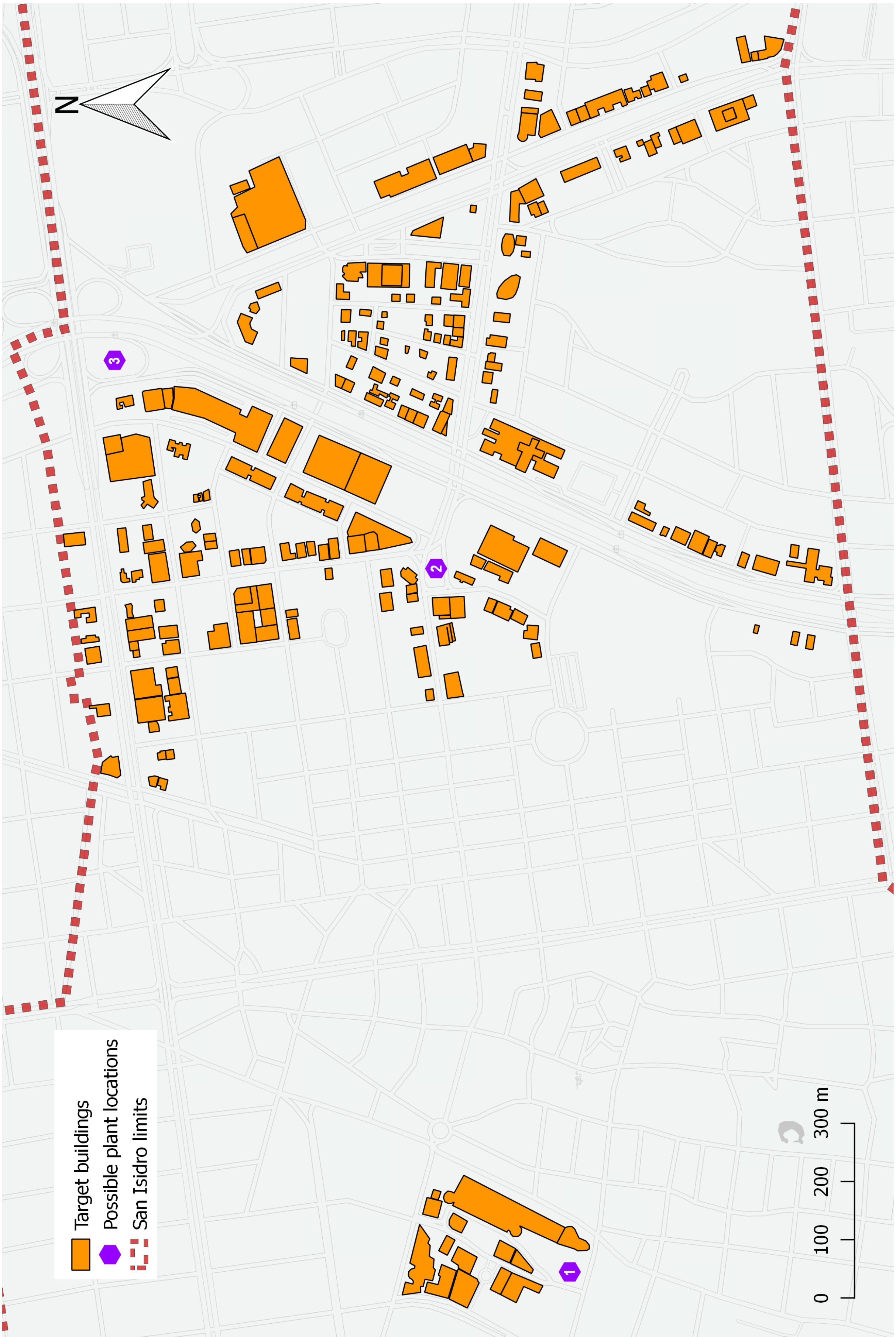

Fig. 6.1.: Overview of potential cooling plant locations in San Isidro.

6.2 Implementation Phases

As mentioned in Section 3.6.1, the development of the system should follow a phased approach, with a gradual implementation of district cooling throughout the district. The Government of Peru is generally reluctant to favor certain kinds of technologies over others when it comes to the private sector, while at the same time they have been implementing energy efficiency measures within the public sector (MINEM specialist, Personal communication, 26. February, 2017). Keeping this in mind it was decided that the first phase of the San Isidro district cooling system wold only target public buildings in the area, and later phases would then grow out of this initial phase.

Fig. 6.2.: Overview of public buildings in the commercial metropolitan zone of San Isidro

Figure 6.2 shows the location of public buildings within the metropolitan commercial zone in San Isidro. As can bee seen on the figure, there are two concentration of public buildings in the area, one in the south-eastern part of the district, and another in the center, directly south of the Centro Financiero de San Isidro where there is a high concentration of cooling capacity. In order to minimize the spread of the initial phase, and in order to keep it close to the main concentration of capacity, it was decided to focus on the public buildings west of, and running alongside, Av. Paseo de la República. Figure 6.3 shows the buildings selected for phase one. As can be seen, this phase is dominated by the Petro Perú building, which is the biggest highlighted building on the map. The total estimated cooling capacity of the buildings selected for phase 1 is 3.33 MW.

Fig. 6.3.: Overview of buildings selected for phase 1

The next step in developing the phases was to review how the system would look in the final phase, and then extrapolate between the first and the final phases. In order to select buildings for the final phase the following guidelines were made taken into consideration

- The system should cover approximately 75% of the cooling capacity in the MCZ of San Isidro.
- The system should be concentrated around the locations with high demand, identified in the capacity demand mapping.
- Buildings with less than 50 kW capacity should not be included, to reduce the need for a unnecessary long network.

The reason for aiming for a 75% coverage of the demand was to account for the fact that not everybody might be inclined to connect to the district cooling system. It might also be necessary to not include buildings that are far away in order to reduce the cost of the distribution network, thus reducing the overall penetration of the system. The same reasoning was used with regards to not including buildings with relatively low cooling demand. Another factor that effected the selection for the final phase of the development was that the special regulatory zone (SRZ) in the west is located approximately 1 km away from the MCZ in the east. Because of this distance, it was decided to develop the SRZ separately from the system in the east instead of connecting them together by a long pipe. The SRZ is thus developed as a secondary site, Site B; while the MCZ is developed in phases 1 to 4, as part of Site A. Following the above criteria resulted in the building selection which can be seen on the overview Figure 6.4. This selection covers most buildings in the northern part of the MCZ but leaves out buildings that have either too small capacity in the center or are relatively far away from where the main capacity is.

When examining which buildings were included in phases 2 and 3, it was decided to focus on integrating buildings close to the phase 1 buildings first, while leaving outlying buildings for later. Streets and junctions were also considered natural barriers between phases.

Fig. 6.4.: Overview of phases 1 to 4 in the development of site A

Figure 6.5 shows the buildings of the special regulatory zone that are selected for for site B. The buildings in this area are all relatively close to each other and have high cooling capacities, so they were all selected as targets for district cooling.

Table 6.1 gives an overview of the estimated capacity of buildings in each phase and the corresponding fraction that the capacity of each phase represent of the total cooling capacity in the commercial metropolitan and special regulation zones.

Fig. 6.5.: Overview of buildings selected for site B

6.3 Distribution Network

6.3.1 Layout

The distribution system was designed so that the layout was first made for the final phase of the project, and then the layouts were made for the earlier phases. Figure 6.6 shows the distribution network layout for phases 1 to 4 of site A, while Figure 6.7 shows the layout for site B.

Tab. 6.1.: Estimated cooling capacity – and thus peak cooling demand – of buildings in each project phase.

	Capacity [MW]	Fraction of Total Cap. of SRZ & MCZ [%]
Phase 1	3.334	4.3
Phase 2	12.825	16.4
Phase 3	28.175	36.0
Phase 4	51.833	66.2
Site B	13.297	17.0
Phase 4 + Site B	65.130	83.4
Total Cap. of the SRZ & MCZ	78.330	100.0

Fig. 6.6.: Layout of the distribution network for phases 1 to 4 in site A

Table 6.2 gives an overview of the length of each diameter pipe that would be used in the distribution network and the total length of the network. Note that the length accounts for both supply and return pipes.

Tab. 6.2.: Total length of different sizes of pipes used in the distribution system

Diameter [mm]	Phase 4 length [m]	Phase A length [m]	Total Length [m]
100	1216	56	1272
125	400	0	400
150	56	194	250
200	2358	210	2568
250	138	194	332
300	1038	232	1270
350	636	0	636
400	266	256	522
450	680	0	680
500	2154	64	2218
600	856	0	856
700	0	0	0
800	144	0	144
Total	9942	1206	11148

Fig. 6.7.: Layout of the distribution network for site B

6.3.2 Pumping Power

Based on the length of the piping network, as presented in Table 6.2, the pressure drop in the pipes was calculated for each phase using Equation 3.7 and Table 3.3 and the pumps were sized accordingly using Equation 3.13. The result can be seen in Table 6.3. Based on this information, the pumps for each phase were sized. Note that a 50 kPa pressure drop over the last substation was assumed when sizing the pumps

Tab. 6.3.: Total installed pump capacity for each phase of the project.

	Phase 1	Phase 2	Phase 3	Phase 4	Site B	Total capacity
Pump power [kW]	186	726	1,594	2,932	109	3,041

6.3.3 Size and Costs

The total investment costs for each phase of the distribution network can be seen in Table 6.4. These costs include labour, supervision and procurement costs for laying two parallel pre-insulated pipes of different diameter.

The procurement and operation and maintenance costs of the circulation pumps for each phase of the project can be seen in Table 6.5.

Tab. 6.4.: Total investment and O&M costs for the piping network for each phase of the project

	Phase 1	Phase 2	Phase 3	Phase 4	Site B	Total
Invest. [US$]	908,517	1,019,489	940,132	1,513,843	433,176	4,815,158
O&M [US$]	4,543	5,097	4,701	7,569	2,166	24,076

Tab. 6.5.: Investment and O&M costs for the circulation pumps during each phase of the project

	Phase 1	Phase 2	Phase 3	Phase 4	Site B	Total
Invest. [US$]	7,745	20,042	40,159	70,001	4,773	142,720
O&M [US$]	232	601	1,205	2,100	143	4,282

6.3.4 Free-cooling

Lima is a city that that sits next to the Pacific ocean, and as such is a candidate for using sea water as a source of free-cooling in order to drive down the operating costs of the cooling system. Cold water could be pumped from the bottom of sea close to Lima, and then used to cool down return water from the district cooling system. The problem with this idea in the case of San Isidro, is that both the Special Regulatory Zone and the Metropolitan Commercial Zone are not adjacent to the ocean, but lay instead several kilometers inland. This would mean that in order to supply the target locations, several kilometers of pipes would need to be laid in order to transfer the water. Two scenarios were considered, one were only Site B would use free-cooling and and another scenario were both Site B and phase 4 care supplied with chilled water produced by a plant located by the sea. The reason for introducing a scenario with only B, and then with both Site B and phase 4, is that Site B which covers the Special Regulatory Zone lays between the sea and the Metropolitan Commercial Zone of phase 4. Note that in the case of the "Site B + Phase 4" scenario there are two different pipe diameters, one for the pipe from the ocean to the SRZ and one from the SRZ to the MCZ.

Tab. 6.6.: Total length, diameters and costs of the pipes supplying the target areas with chilled water from a plant by the sea.

	Site B	Side B + Ph.4
Length [m]	3248	3248/1428
Diameter [mm]	500	1100/1000
Costs [US$]	4,248,384	13,034,812

Table 6.6 shows the distance, diameter and total investment costs for the piping network that would supply the scenarios. The investment costs for the phase A scenario pipe is US$4,248,384 while the investment cost for the phase A+4 scenario is US$13.034,812. Contrasting these costs with both the total plant and total system costs for the other scenarios presented in Section 6.6 shows without further analysis that even though the variable operating costs of a plant utilizing free-cooling would be lower a plant using other methods, the high cost of transporting the chilled water to the target areas is too

high for this type of system to be a viable alternative. Thus, a system utilizing free-cooling was not investigated further in this project.

6.4 Cooling Load Profiles

Cooling load profiles were created for each phase based on the peak cooling capacity, occupancy hours and cooling degree hours for the reference year 2016. To account for the difference in occupancy hours for offices and hotels, the capacity ratio between these two building usage types was calculated for each phase and are presented in Table 6.7.

Tab. 6.7.: The capacity ratio between offices and hotels for each phase

Phase	Offices	Hotels
1	100%	0%
2	100%	0%
3	91.8%	8.2%
4	95.3%	4.7%
Site B	93.8%	6.2%

As can be seen in Table 6.7, office type buildings dominate all phases, and thus the fact that hotels have constant occupancy – compared to offices which are only occupied between 8 and 18 – has only a small effect on the load profiles. Figure 6.8 shows the one year load profile for Phase 4. The load profiles for phases 1, 2, 3 and Site B look almost identical sake for the scale of the cooling demand and the slight effect of the hotel load during hours when offices are not occupied.

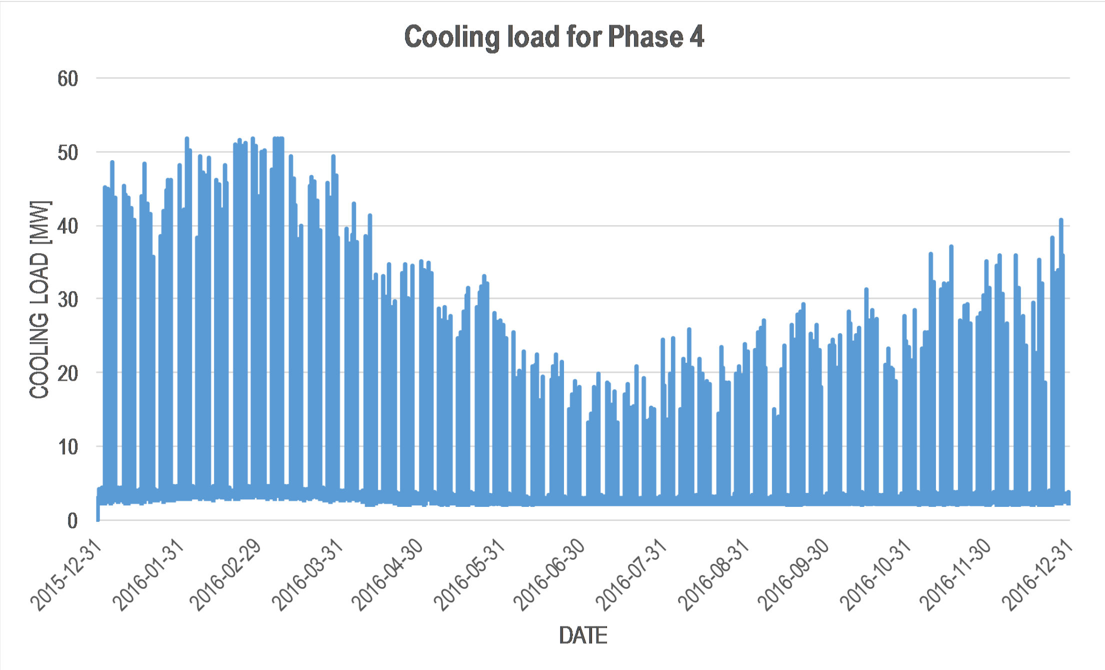

Fig. 6.8.: The load profile for Phase 4, in Site A, over a whole year.

Finally, the annual cooling load and peak load estimates were extracted for each of the generated cooling load profiles. These are presented in Table 6.8.

Tab. 6.8.: Annual cooling loads and peak loads for each of Site A's phases and for Site B.

Load Type	Annual Cooling Load [MWh]	Peak Load [MW]
1	4,887	3.33
2	19,499	12.83
3	45,391	28.18
4	81,473	51.83
Site B	21,124	13.30

6.5 Chiller Plant and Storage Sizing

On the basis of what has been described in the technology overview in Section 2.2, the assessment of the district cooling systems contemplated chiller plant options along with thermal energy storage. The preliminary system design considered three different storage sizing approaches, as initially described in Section 3.6.7: Full storage, Partial Storage, and No Storage.

For the case of partial storage, 3 additional scenarios were considered because of the lower requirement for both chiller and storage capacity obtained with this sizing method. These corresponded to 30%, 20% and 10% storage discharge capacity during the peak period considered in the design, while the reference partial storage scenario corresponded to a 55% of storage discharge capacity during peak.

Each of these sizing approaches resulted in different chiller capacity estimates, derived from the cooling load profile in Phase 4 of Site A, and in Site B. A summary of these configurations and their results are presented in Table 6.9 and Table 6.10. As expected, the partial storage approach allowed for a better balance between the chiller plant cooling capacity and storage capacity, with the reference partial TES case having the lowest capacity required by the chiller.

Tab. 6.9.: Configurations of chiller capacities and corresponding thermal energy storage capacities and volumes, for the plant in Site A.

	Full Storage	Partial Ref. - 55%	Partial 30%	Partial 20%	Partial 10%	No Storage
Chiller Capacity [MWh]	32.2	24.1	36.3	41.5	46.7	51.8
Storage Capacity [MWh]	371.3	266.7	133.1	79.1	34.5	-
Cold Store Volume [m^3]	39,962	28,704	14,325	8,514	3,715	-

From this estimates, it can be noted that lower storage capacities are demanded by partial TES when contrasted with full storage sizing, despite similar chiller capacities. Likewise,

Tab. 6.10.: Configurations of chiller capacities and corresponding thermal energy storage capacities and volumes, for the plant in Site B.

	Full Storage	Partial Ref. - 55%	Partial 30%	Partial 20%	Partial 10%	No Storage
Chiller Capacity [MWh]	8.0	6.0	9.31	10.6	11.97	13.3
Storage Capacity [MWh]	96.6	70.6	34.14	20.3	8.9	-
Cold Store Volume [m^3]	10,392	7,594	3,675	2,184	953	-

the estimated cooling capacity of a chiller plant in lower partial storage cases shows, as illustrated in Figure 6.9, chiller capacity being inversely proportional to storage.

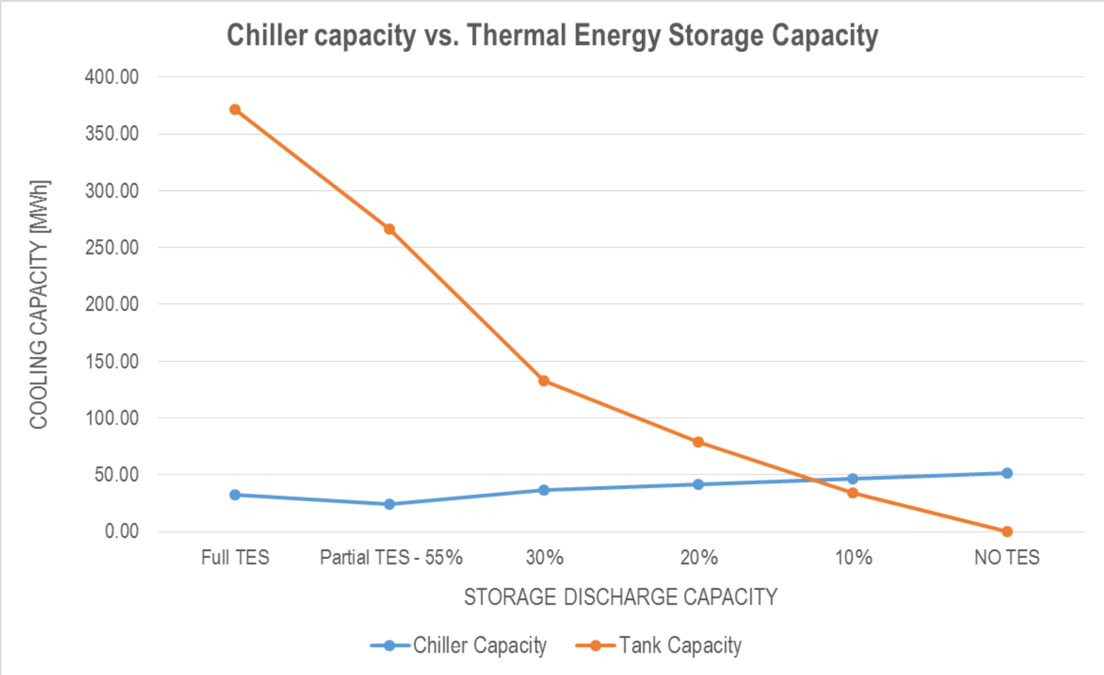

Fig. 6.9.: Capacity of chillers sized accordingly to storage discharge capacity, for Site A

The chiller and storage configuration can be expected to affect the operations of the complete district cooling system. For example, under the "No Storage" case presented, the cooling output from the chiller plant will be made to follow directly the total cooling load. This in turn, requires higher chiller capacities with their correspondingly high investment and operational costs. Moreover, it would require high output variation between operating at lower loads and at peak loads, which may proof highly inefficient for the plants (Frederiksen and Werner, 2013). On this basis, the configurations of cooling storage could provide a degree of flexibility and higher efficiency to the system's operations that would also be reflected in the total economic costs of the system.

Figure 6.10 illustrates how such a lower chiller capacity system would function with thermal storage. Here it can be seen, for the partial storage reference case, that the cooling output generated by the chiller plant is significantly lower than peak cooling demand, for the hottest week of the year. However, the operations of the chiller extend beyond peak hours, thus shifting part the energy requirements for cooling generation out of peak hours. During these peak periods, cold storage covers the remaining cooling load not met by the chiller. Past this point, the continuous operations of the chiller plant at its design capacity allow for it to operate efficiently and recharge the cold store reserves.

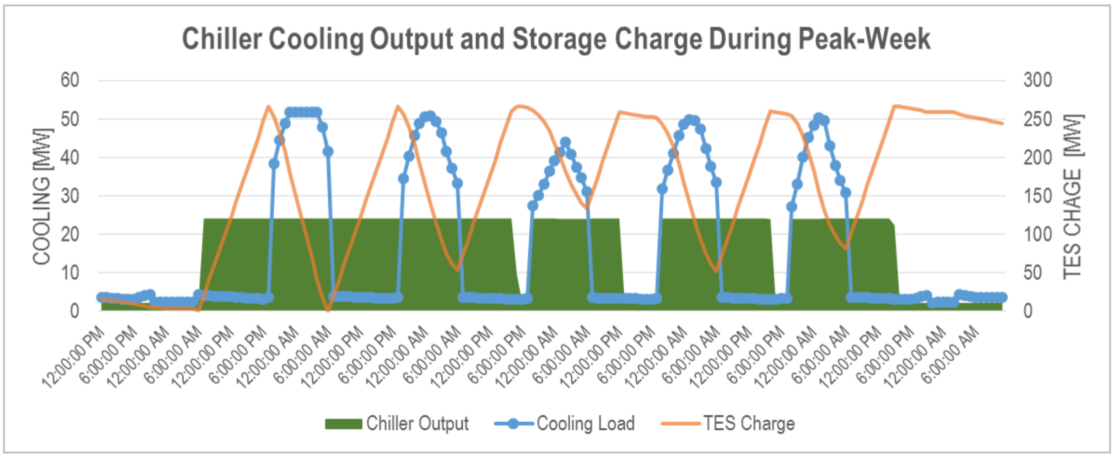

Fig. 6.10.: Chiller and storage operations during the hottest week of the year, in week 13 of 2016, considering the partial TES case.

The operations under chiller and storage configurations will change throughout the year according with the existing seasonal need for cooling, as shown already in Figure 6.8. During the warmest period of the year, the chiller plant will run at maximum capacity in tandem with the cold store supply. Subsequently, during lower demand periods, the cooling load can mostly be supplied by the stored cold reserves or by the plant running at lower output capacities, which may be the case during base load periods.

6.6 Total System Costs

Based on the plant configurations presented in the previous section, the capital investment, and operational and maintenance costs for all phases in Site A and Site B were calculated. These estimates, as per the procedure explained in Section 3.7.3, were derived from the plants' capacities; and considered the investment costs of chiller plants, storage, cooling towers, auxiliaries and electronic components, as well as the maintenance, operational, water and energy costs. These were then added to the distribution network costs presented in Section 6.3.3, to estimate the total cost of each system alternative.

These costs, presented in Table 6.11 and Table 6.12 for Site A and Site B, respectively, represent both the total discounted capital and operating expenditures incurred during the 20 years of economic lifetime assumed for the project.

Tab. 6.11.: Discounted investment and O&M costs of each system configuration corresponding to Site A.

Configuration	Plant w/ Electric Chiller Invest. [million USD]	Plant w/ Electric Chiller O&M [million USD]	Plant w/ Absorption Chiller Invest. [million USD]	Plant w/ Absorption Chiller O&M [million USD]
Full TES	17.44	8.09	20.93	13.9
Partial TES - Ref.	13.37	7.81	16.08	13.40
Partial TES - 30%	15.25	7.40	19.46	12.68
Partial TES - 20%	16.05	7.30	20.86	12.49
Partial TES - 10%	16.99	7.19	22.41	12.32
NO TES	18.3	7.08	24.1	12.14

Tab. 6.12.: Discounted investment and O&M costs of each system configuration corresponding to Site B.

Configuration	Plant w/ Electric Chiller Invest. [million USD]	Plant w/ Electric Chiller O&M [million USD]	Plant w/ Absorption Chiller Invest. [million USD]	Plant w/ Absorption Chiller O&M [million USD]
Full TES	9.21	4.3	11.44	7.45
Partial TES - Ref.	6.93	4.21	8.61	7.35
Partial TES - 30%	8.02	4.08	10.63	7.23
Partial TES - 20%	8.49	4.09	11.46	7.18
Partial TES - 10%	9.04	4.05	12.38	7.21
NO TES	9.67	4.02	13.39	7.18

Implementation Scenario 7

This chapter builds up on the analysis previously presented in Chapter 6, by examining the economic performance of the complete district cooling system under a potential implementation alternative. A sensitivity analysis of key technical and economic parameters will also be presented, which will provide insights into how the system might respond under different conditions. Altogether, the analysis will shed light on the following research question:

4. What are the economic cost benefits of a district cooling implementation?

7.1 Implementation Case

From the results presented in Section 6.6, the favorability of the electric chiller plant with partial storage becomes apparent, specially for the reference case of 55% storage discharge capacity. By order of merit, as seen in Table 7.1, this scenario results as the most cost effective for both sites, yielding a net present cost of $21,080,350.20 USD, under a discount rate assumption of 4% over a 20 year project lifetime. .

Tab. 7.1.: Net present costs of each system configuration corresponding to Site B.

Configuration	Site A: Phase 1-4		Site B	
	Electric Ch. [million USD]	Absorption Ch. [million USD]	Electric Ch. [million USD]	Absorption Ch. [million USD]
Full Storage	25.44	34.68	13.20	18.37
Partial TES, Ref.	21.08	29.33	10.84	15.45
Partial TES - 30%	22.56	32.00	11.82	17.35
Partial TES - 20%	23.25	33.21	12.29	18.14
Partial TES - 10%	24.10	34.58	12.80	19.09
No Storage	25.29	36.10	13.40	20.07

The resulting cost comparison of the different options, seen in Table 7.1, shows that the electric chiller plant options outperform absorption chiller plants in terms of costs, regardless of storage configuration. However, for both types of chiller plant scenarios, the reference partial storage option — which has the lowest chiller capacity — is the least costly option. Thus, it was considered as the base district cooling implementation scenario in subsequent analysis. A complete summary of the cash flows for this scenario is presented in Appendix A, for further consideration.

The difference in cost performance for the scenarios can be traced back to the type of expenditures associated to each plant and storage configuration, as Figure 7.1 illustrates for the electric chiller case in Site A.

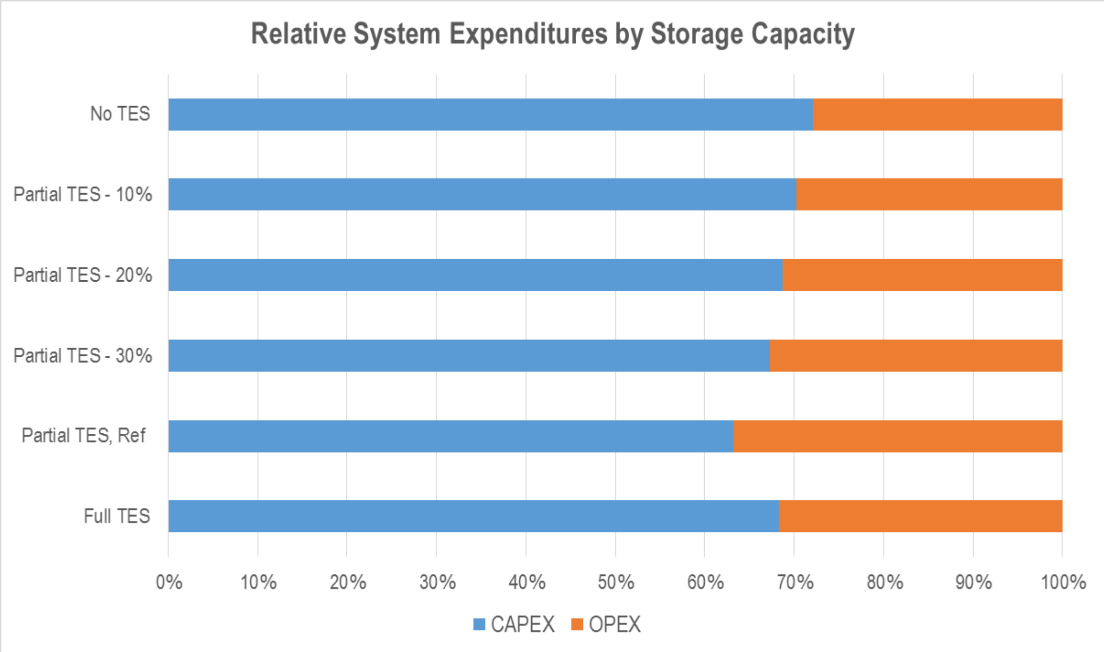

Fig. 7.1.: Relative capital and operational expenditures for each thermal energy storage option presented for an electric chiller plant.

From this, it can be observed that the configurations with higher proportions of capital expenditures are, correspondingly, more costly. In absolute terms, this doesn't necessarily mean that operational costs are higher for the reference partial storage case, but rather that they constitute a bigger share of total costs because of the overall lower capital expenses incurred by the system. Thus, it can be inferred that capital expenses are the main key driver behind overall system costs.

The cost breakdowns presented in Figure 7.2 better illustrates the above-mentioned observation. As can be seen for the base implementation case, the combined costs of the chiller plant, storage, distribution network and the investment contingency assumed, largely outweigh the total operational costs. In terms of the latter, which are constituted by the system's energy costs and the operation and maintenance of the system components, the energy costs are the main cost contributor to this cost group.

The relative difference in cost groups between Site A and Site B must also be noted, namely corresponding to the share associated to the cost of the distribution network. This difference can be attributed to the phased approach, and overall larger network considered in Site A. Site B's network in contrast, is limited to a single phase, in a more confined area, which clearly reflects in the overall cost breakdown.

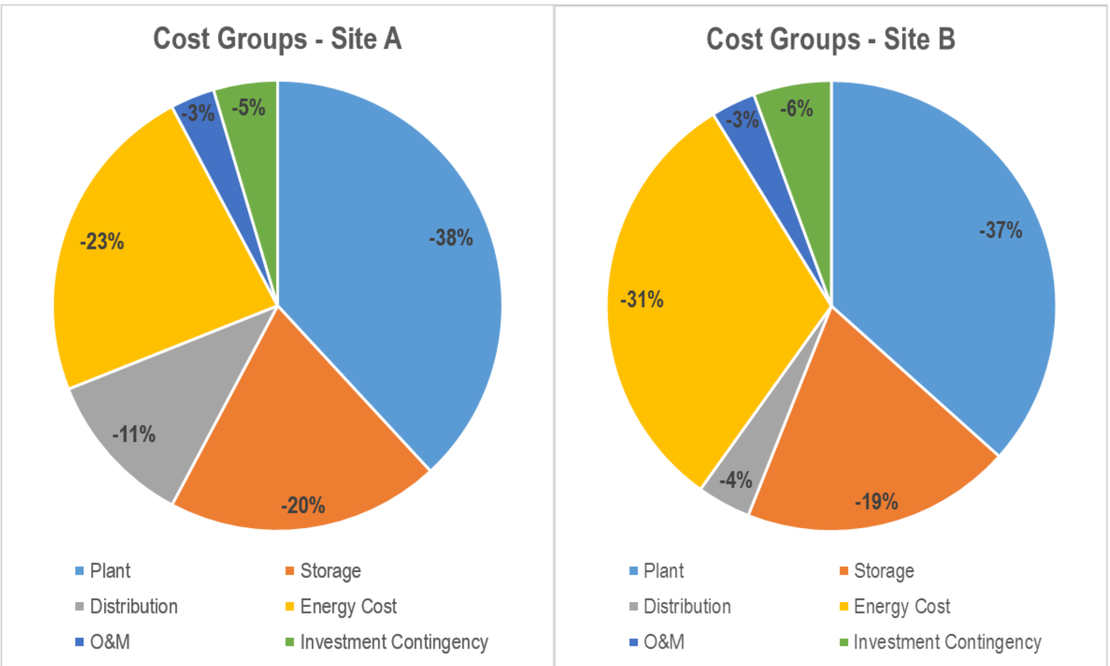

Fig. 7.2.: Relative cost breakdown by cost category groups for Site A and Site B.

In connection to Site A's phases, the distribution of the aforementioned costs will also change throughout the total time span of the project. Initially, the capital cost components will be of most impact, and constitute a larger share of the total net present costs. In time, recurring operational expenses will have a greater effect on the system.

Figure 7.3 clearly shows this cost evolution, by contrasting the cost shares of capital and operational expenditures throughout the different phases. It is important to remember, as stated in Section 3.7.5, that at the last year of the projects' economic assessment an additional cost item related to the salvage value of equipment must be considered. This is due to the fact that different components in the system have different economic and technical lifetimes, and the salvage value enables the proper comparison between components added to the system at different time periods along the phases. This additional expenditure acts as a counter to the capital expenditures estimated for Phase 4, since several system components have lifetimes exceeding that of the one considered for the economic evaluation. Naturally, this ameliorates the effects of new capital expenditures in Site A's phase 4. However, the effects are not as noticeable in Site B, where most of the capital investment takes place in the initial year, and no subsequent phases are present.

The comparison made thus far between Site A and B, while accounting for overall system costs does not readily show another intrinsic component of the systems, which is the total energy output that each of these alternatives have. In view of this matter, the net present costs already mentioned were further analyzed in conjunction with the total cooling output expected over the lifetime of each plant, based of the annual cooling

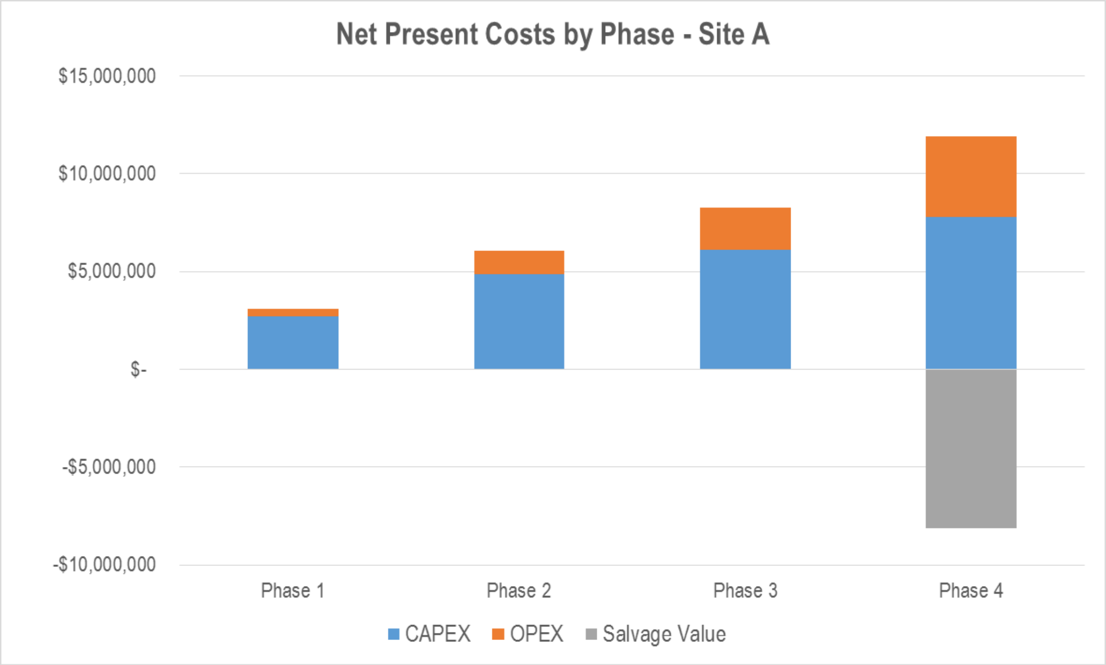

Fig. 7.3.: Evolution of capital and operating expenditure by phase in Site A.

load estimates presented in Section 6.4. This resulted in the levelized costs of cooling presented in Table 7.2, which serve as an indicator of the cost of producing a unit of cooling capacity. In other words, the minimum cost of cooling for the systems to break even at the end of the projects lifetime.

Tab. 7.2.: Levelized costs of cooling for each system configuration.

Scenario	LCOC - Site A [USD/MWh]	LCOC - Site B [USD/MWh]
Implementation Scenario (Partial TES, Ref.)	43.90	37.78

7.2 Consumer Alternatives: Business-As-Usual and District Cooling Provision

In addition to the previous economic indicators of the project, the consumer economic benefit had to be addressed to determine how the district cooling implementation fares in comparison to current approaches. To do so, a Business as Usual (BAU) scenario was considered from a consumer perspective. That is to say, the perspective of the bulk of targeted buildings with the options to either develop an on-site cooling solution, or the option of paying for the district cooling supply provided by the implementation scenario.

The BAU scenario, constructed as per Section 3.8.1, parted from the assumption of the bulk of consumers initially investing for an onsite electric chiller system, with its associated operation and maintenance costs over the same 20 year project lifetime as that used for Section 7.1. The cash flows of these two scenarios is present in Table 7.3, for the case of Site A.

Tab. 7.3.: Life-cycle costs of the BAU scenario and District Cooling Connection scenario.

Business as Usual	Year 0	1	2	...
Chiller & Equipment Installation [USD]	41,261,564	-	-	...
Operation & Maintenance [USD]	-	62,775	62,775	...
	...	18	19	20
Chiller & Equipment Installation [USD]	...	-	-	(5,002,745)
Operation & Maintenance [USD]	...	62,775	62,775	62,775
	Net Present Cost= $39,831,516			
District Cooling Connection	Year 0	1	2	...
Investment Savings [USD]	(41,261,564)	-	-	...
O&M Savings [USD]	-	(62,775)	(62,775)	...
District cooling purchase [USD]	3,573,960	3,573,960	3,573,960	...
	...	18	19	20
Investment Savings [USD]	...	-	-	5,002,745
O&M Savings [USD]	...	(62,775)	(62,775)	(62,775)
District cooling purchase [USD]	...	3,573,960	3,573,960	3,573,960
	Net Present Cost= $12,304,942			

The cost for the BAU scenario, in Table 7.3, are displayed according to their expenditure type; that is, the capital expenditures incurred in the acquisition and installation of chillers and other equipment, and the operation and maintenance costs, which also include the cost of electricity needed by the cooling equipment. The district cooling connection scenario, on the other hand, presents the expected savings of not having to pay for the costs described above, while adding the actual costs incurred in the purchase of the cold supply from the district cooling system.

The cost for purchasing from the district cooling system considered a price equal to the levelized cost of cooling, presented in Section 7.1. This was considered since it would be the minimum starting price that a provider may consider to pay off the investment of the district cooling implementation as such.

The results presented in Table 7.3 correspond to the expected cash flow for both scenarios, for the case of Site A. Yielding a net present cost of 39.83 and 12.30 million USD for the the BAU and District Cooling scenarios, respectively. This assumed the purchase of cold supply at a rate of 43.87 USD/MWh, equal to LCOC of the implementation.

For Site B, the approach resembled that presented above. The estimates for Site B yielded a net present cost of 13.25 and -2.23 million USD for the the BAU and District Cooling scenarios, respectively, with a cold supply price of 37.78 USD/MWh, equal to the LCOC of the implementation case for this site. It must be noted, as explained in Section 3.8, that the negative net present cost estimated for the district cooling connection actually translate into a positive net present value. That is to say, it represents a capital gain from the expected savings that purchasing from the district cooling system provides the consumers in Site B, under the given cooling cost assumption.

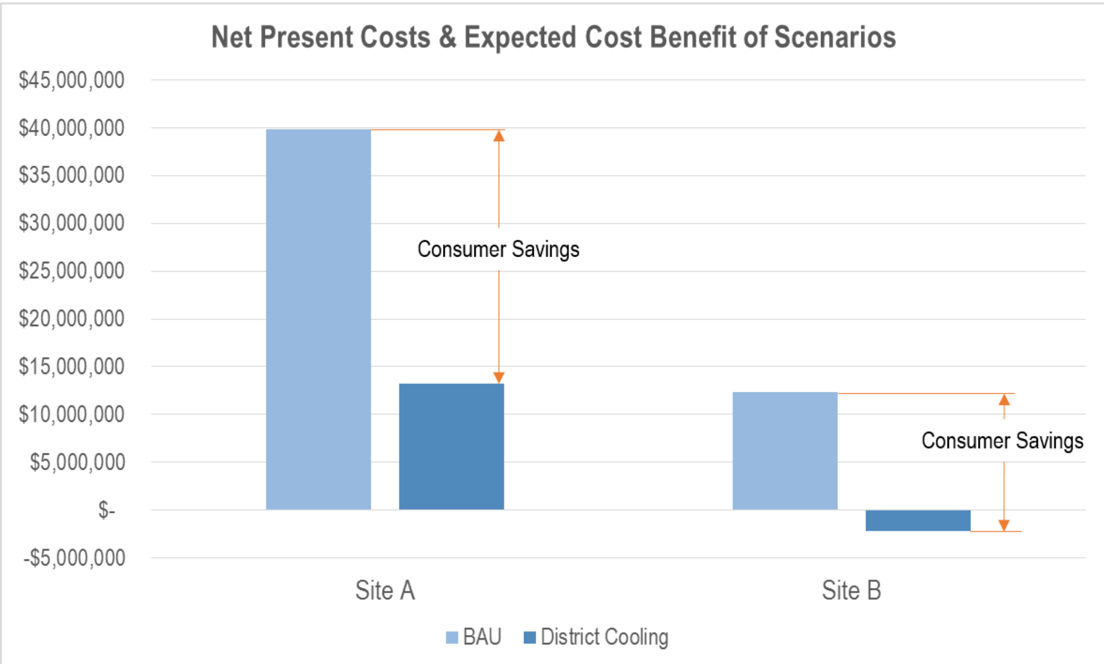

Fig. 7.4.: Cost situation and consumer benefit with cooling alternatives.

The differences between net present costs estimated between each scenario, can then be represented as the costs savings for the consumers. Figure 7.4 provides a visual representation of these net present cost savings for both Site A and Site, and their respective BAU and District Cooling Scenarios. The savings from connecting to the district cooling system amount to 26.59 and 14.53 million USD for Site A and Site B, respectively.

7.3 Sensitivity Analysis

7.3.1 Impact of Consumer Alternatives on the Implementation

The scenarios present in Section 7.2 used as reference cooling prices the levelized costs of the systems. However, using these levelized costs as reference prices did not account for any additional profit that could be made with the district cooling system.

To further determine an allowable margin of profit before the district cooling alternative becomes as expensive as the BAU scenario, the cooling prices were sensitized. This sensitivity analysis consisted of finding a net present cost under which both the BAU and the District Cooling connection scenarios were the same, by changing the cooling price. This cooling price calculation was then added as a revenue stream to the cash flow calculations of the original implementation scenario presented in Section 7.1. The net present value and the discounted payback time of the system was then determined. These results are presented in Table 7.4.

Tab. 7.4.: Sensitivity table for maximum allowable cooling price, and expected payback time with the additional revenue from cooling sales.

Site	Base Price [USD/MWh]	Max. Allowable Price [USD/MWh]	NPV@ Max. Price [million USD]	Payback [years]
Site A	43.90	67.02	11.11	18.4
Site B	37.78	87.98	14.41	5.2

7.3.2 Impact of Cost Assumptions

Preluding the aforementioned results, a number of assumptions on different parameters had to be made. Due to these inherent assumptions, and in order to better understand the effect of more specific cost components on the overall economics of the system, the results for the implementation scenario originally presented in Section 7.1 were further assessed by analyzing the effect of uncertainty on the following:

- Total installation costs of the chiller plant, cooling tower, electric equipment, and auxiliaries
- Storage costs
- Total installation costs of laying piping for the distribution network and pumping equipment
- Energy (electricity) cost
- Operation and maintenance costs
- Salvage value as a percentage of initial costs

- Investment Contingengy
- Discount Rate

The results of this sensitivity analysis are presented in terms of net present cost in Figure 7.5 for Site A.

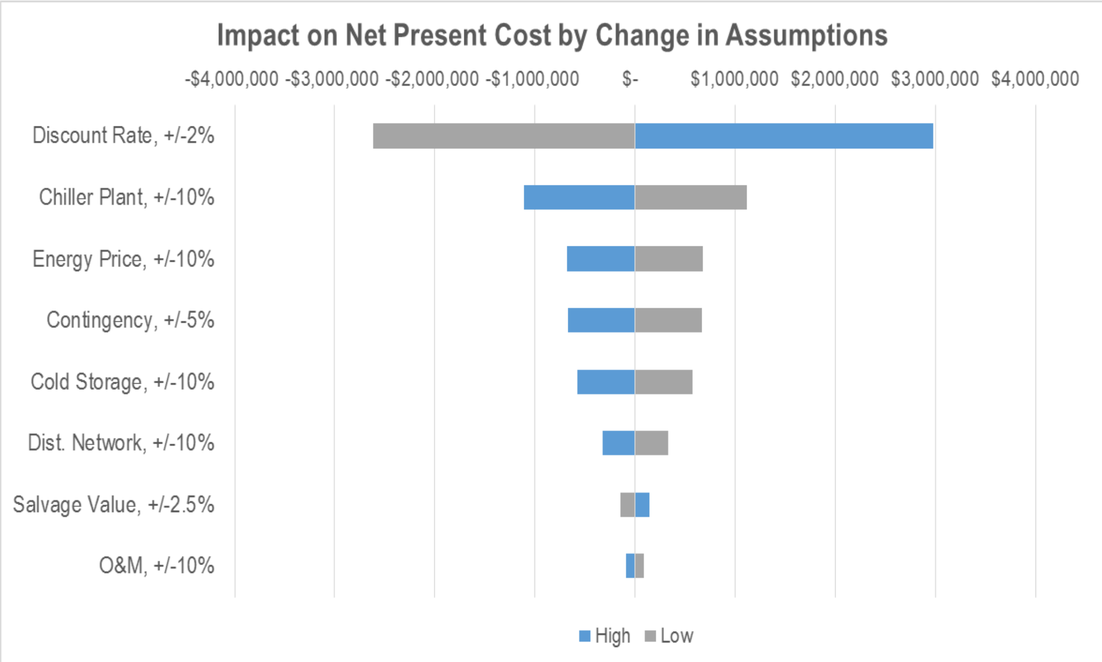

Fig. 7.5.: Sensitivity of Net Present Cost by Variations in Key Parameters, for Site A

As can be seen from Figure 7.5, the degree of sensitivity of the results varies from parameter to parameter, and even within the range of a single parametric change. For instance, in Site A the effect of changing the base assumption of a 4% discount rate by 2%, represents a change of up to 2.98 million USD if, instead, a discount rate of 6% is used. On the other hand, a lower discount rate consideration favors the economics of the project by reducing the net present costs by 2.62 million USD. That is to say, an expected increase of 14.2% or a decrease of 12.4%, may be expected by either a positive or negative 2% variation in discount rate assumption.

The economics of the project in Figure 7.5 can also be seen to be more sensitive to those parameters described in 7.1 as having cost components with larger shares of the total net present cost. Clearly, the impact of chiller plants, storage and energy prices have larger impacts than, for instance of O&M cost or the gains from components' salvage values.

From this, it can also be deduced that changes in discount rate are, in Site A, by far more significant to the net present cost end results than changes in other cost assumptions. A possible explanation for this is the amount of discounted cash flows in the economic calculations, stemming from the multiple investments that come into play in future phases along the lifespan of the project, and thus are more affected by discounting.

The above-mentioned observation regarding the effect of future investments comes into light when comparing the impacts of the same parameters on the economics of Site B, where no phases are to take place in future stages. Figure 7.6 shows this, when contrasting the lower sensitivity of the net present cost to changes in discount rate assumption.

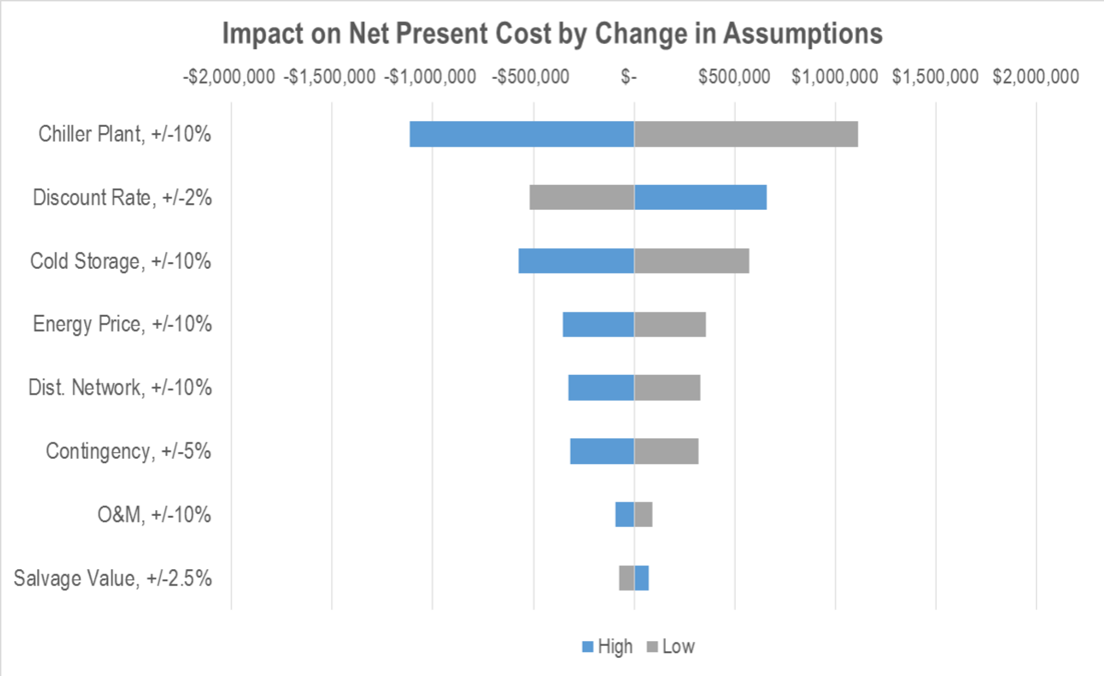

Fig. 7.6.: Sensitivity of Net Present Cost by Variations in Key Parameters, for Site B

In Site B, the effect of discount rates remains high, however the model is more sensitive to chiller plant cost assumptions. A 10% variation in chiller plant costs, translate to approximately a 1.11 million USD change in net present costs, which is to say a 6.2% net present cost variation from the base case scenario.

Overall, the uncertainty of some of these cost assumptions may greatly affect the economics of the project and would also translate to different pricing potential as that presented in Section 7.2. In terms of levelized costs of cooling, considering the parameters with highest impact for each of the two Sites yields changes in excess of 6.21 USD/MWh and 3.88 USD/MWh, for the LCOCs in Site A and Site B, respectively. This, logically, would also have to be factored into the final price valuation for each site.

A complete summary of the sensitivity analysis outputs is present in Appendix A, for further consideration.

8 Recommendations and Discussion

This chapter brings together the topics and results from the preceding chapters, by prompting a discussion about potential recommendations that can be made in order for a district cooling implementation to occur, and by touching upon key aspects and limitations stemming from the analyses so far presented. In doing so, this chapter will answer the following research question:

5. What policy suggestion could further the development of a district cooling system in Lima?

8.1 Policy Suggestions

Following the policy and institutional analysis in Chapter 4, the cooling mapping showcased in Chapter 5, the system modeling described in Chapter 6, and the economic analysis laid out in Chapter 7; this section presents some suggestions stemming from the above-mentioned analyses. These policy recommendations are:

- *Consider district cooling as a potential project initiative under the framework of energy efficiency, sustainable constructions, NAMAs and local sustainability*
  As explored in Chapter 4, existing policy and institutions relate to a district cooling implementation on multiple fronts. Thus, the different institutions should coalesce around their priorities, their policy tools and expected gains, in order to allow for a district cooling initiative to take place.

- *Utilize energy mapping as a tool for assessing the potential of district cooling in urban areas*
  Energy mapping served as a powerful tool by which to identify the potential of cooling in the district, as Chapter 5 showed for the particular case of San Isidro. Its application is generally used as a tool for decision makers to identify the potential of district energy in urban areas (UNEP, 2015). Hence, it should be considered as such in order to identify the district cooling potential in the city, and in the Peruvian territory.

- *Work on the promotion of district cooling benefits with society at large, and potential project developers and consumers*
  Through the existing policy applications and institutional approaches explored in Chapter 4, the benefits of district cooling could be made widespread. These benefits, including those outlined in Chapter 7, may serve as show cases to incentivize potential parties to undertake district cooling projects, or join future systems. In this regard, an implementation starting with public consumers, as was proposed in Chapter 6, may serve as both an initial implementation phase, and more importantly as a "proof of concept" for interested parties. In the same manner, promotion mechanisms may serve as a way to engage society at large, and mitigate any adverse effect that a district cooling implementation may have.

8.2 Benefits of Implementation

The benefits of implementing this project need to be analyzed from the perspectives of different stakeholders, since their gain from the project varies quite significantly. The stakeholders that stand to gain directly financially from the implementation of the district cooling system are on the one hand the building owners and developers, and on the other hand the owners of the system. As presented in Section 7.2 the net present cost of the district cooling system is significantly lower than the business-as-usual case, and it stands to reason that this type of implementation may constitute significant cost savings for building owners and developers. It has though to be noted that the costs savings for end-users need to be balanced with the payback time of the investment for the owners of the district cooling system in the case of those two parties not being the same. Greater cost savings for building owners and developers translate to lower profits for the owners of the system, and depending on the ownership structure a certain payback time might be required in order for the project to be considered viable.

Besides direct financial benefits of the system there are stakeholders that can benefit from the it in other ways. Because of the load shifting effects of a district cooling system with thermal energy storage, the system can reduce the peak electricity demand in the district while the overall energy consumption stays the same. For the electric utilities supplying the district, a more even electricity load could translate to lower costs as electricity transport infrastructure and production plants would not have to supply as large peaks, and be able to operate with higher capacity factors. However, potential decreases in electricity sales, might also deter them from this option. In a future scenario where more renewables would be introduced into the Peruvian energy mix, it is also possible that a district cooling systems with thermal energy storage components could become important in balancing volatility in the electricity system.

8.3 Discussion

8.3.1 Ownership structure

The ownership of the system presented in this report is an important topic to consider. There are three main ways in which a district cooling system could be built and maintained; a private enterprise, a public-private partnership, or as a public utility (UNEP, 2015), and each one of those structures offers certain advantages and disadvantages in the context of Peru. Separate ownership models can also be applied to different phases of the project such as construction and operation.

The systems presented in this report, named Site A and Site B respectively, have some differences that might influence the ownership structure applicable to each. As covered in Chapter 7, Site A is expected to have a payback period of about 18.4 years for the maximum allowable price of cooling, while Site B has a payback period of only 5.2 years. Private enterprises often have a requirement to have relatively fast returns on their investment, and, in that sense, only Site B might be considered as a good investment from a private standpoint. Site A on the other hand has a payback time that is approaching the lifetime of the project which makes this site unattractive as a privately funded investment, but might make sense as a public infrastructure project. Besides the payback time, there are other factors that affect the possible ownership structure. The preferred location for Site A is located on public land and the first phase of that project targets only public buildings, so making this as a public investment might be fitting. Site B on the other hand is located on private land in the Special Regulatory Zone that contains only private enterprises and combined with the short payback time it might make sense as a private project, if it proves more profitable than other asset development options.

Even though Site A might favor public investment initially it might still be relevant to add some sort of public-private partnership to the project for a few reasons. The latter phases of Site A target exclusively private buildings, so some sort of partnership with building owners regarding the expansion of the district cooling network might be relevant. It is also possible that even though the ownership and investment in the system would be public, the running and operation of the system would be private.

8.3.2 Project Limitations

Even though the aim of this project has been to do a thorough analysis of the merit of developing a district cooling system in the San Isidro business district of Lima, there are some limitations to the project that need to be analyzed.

The target location of this project has been the San Isidro district of Lima, and more specifically the Special Regulatory and Metropolitan Commercial Zones of the district. The rationale for focusing on these two zones within the district is that these zones contain high value real estate, office buildings and hotels, that utilize some kind of HVAC systems. Limiting the analysis to these zones has though excluded a lot of buildings in adjacent zones that might well have been candidates for using district cooling. A project analyzing the potential of setting up a district cooling network spanning the whole district, or even including buildings in adjacent districts, might give a result that yields better economic results, but would at the same time require a more thorough analysis of the potential of buildings in other zones to connect to a district cooling network. Including buildings in other districts would in the same way require a deeper analysis of cross district cooperation, which the initial analysis of the institutional barriers points as a mayor structural challenge in the existing framework conditions. Legal issues regarding permitting were not touched in depth; and although special permitting restrictions exist on certain industrial applications and utility provisions, an specific category related to district cooling does not (MSI, 2009).

When it comes to the technical aspects of this project there are several limitations that should be noted. The design of the system is not very detailed from a technological standpoint since a detailed technological design would be out of scope of this project. The design does not consider aspects such as auxiliary equipment, controls, valves, substations and etc. directly. Another technological simplification is that the COP of chillers analyzed in this project is considered to be constant, even though it is dependent on ambient temperature. The rationale for this decision was that the COP values used represent average values of the COP as it changes throughout the year.

When the cooling energy demand of buildings in Lima was assessed the weather situation was compared to other cities with known cooling demand per square meter of office buildings and then data used from cities that had the similar temperature situation according to the ASHRAE design standards. The problem with this approach is that the cooling demand of buildings is not only dependent on external temperatures but also on the building envelope itself, which might differ somewhat between cities and countries. Thus in order to get accurate data about the cooling energy demand of buildings in San Isidro it would be necessary to analyze the building envelopes and the occupancies of the buildings being considered for cooling, and further analyze Peruvian building regulations. Given the fact that there were originally 223 buildings under consideration in the district, this would have been a project on its own.

When it comes to factoring in costs, there are some potential costs that this project leaves out or does not look into. It has been assumed in the project that land that is necessary for this project is already owned by the municipality or the relevant parties, thus it was not counted in the total costs of the project. It has also been assumed that the selected plant locations are viable for the construction of cooling plants without further investigating if the land and the surrounding areas permit the construction of a district scale cooling facility. Societal costs, such as the potential loss of public spaces to infrastructure is also not quantified in this project. This project does not analyze the potential social cost of developing the system. For this project, these costs would mainly include the potential loss of public spaces to cooling infrastructure and possible costs associated with traffic and general disturbances caused by construction.

Cost data for this project is also limited in the sense that it does not necessary reflect the correct prices for the case of Peru. This is in part the result of the lack of district energy projects in Peru. When Peruvian prices were not available prices from district energy projects in Colombia were used, but for some costs it was necessary to use western or international price estimates. The result of this approach might cause the total cost of the project to be overestimated somewhat, although it can also be assumed that since this is the first district energy project to be conducted in Peru the price might rise due to unforeseen reasons.

Finally, this projects assumes that the adoption of district cooling by building owners would follow the phases as they are presented here in this report. This though, might be unrealistic since developers might be reluctant to connect to the system from the get-go; for example, if their currently installed HVAC systems have not reached the end of their lifetime. Building owners might also value the freedom of running their own systems over being obliged to buying cooling from a third party. A market would be needed, in order to better understand this untapped consumer potential.

8.3.3 Further Work

This report has presented, in broad terms, the feasibility of implementing district cooling systems in the San Isidro district of Lima. In the case that this project would be implemented or that the feasibility of it would be further investigated there are certain aspects that would be important to look at.

As covered in Section 8.3.2 the analysis of the cooling demand in San Isidro is done by comparing Lima with other cities considered to have similar climate conditions, and not by directly analyzing the situation on the ground in the city. A more thorough analysis of the cooling demand should be conducted which would entail analyzing the demand on a building level in order to create a better load profile for the system. This load should account for the different types building envelopes and the thermal inertia of the buildings.

The analysis of the system in this report concluded that the optimal technology for district cooling would be some kind of electrically powered vapor compression chillers, but the details of that technology where not investigated further. Looking into the details about different types of vapor compressor technology would be necessary before the project would be implemented. In turn, this would lead to detailed design of the systems.

The phased approached and growth of the district cooling system was based on a number of assumptions, starting from the case of only public buildings joining the system. A more detailed market study, and survey of the existing equipment would be needed to provide more precise estimates of the potential market and costumer growth.

Further interaction with government entities, real state developers and utilities could provide new avenues for exploring district cooling in other sites and sectors. For instance, the potential could perhaps be better realized in new residential projects, and could thus serve as a gateway for democratizing space cooling in the residential sector.

9 Conclusion

This thesis project centered its attention on exploring the potential for implementing district cooling in Lima. The role of the institutions and existing policy was examined, followed by the analysis of a theoretical implementation case in the city's financial district, where a critical mass of the cooling load in the city can be found. Thus, the report looked into some of the institutional, technical, and economic challenges faced by such a district cooling implementation with the goal of answering the following research question:

Is the provision of district cooling for public and commercial buildings in Lima's financial district a viable alternative under Peru's current institutional context?

Correspondingly, the key finding was that the provision of district cooling may be viable in some respects, but not completely on others. District cooling may provide advantages in terms of economic cost benefits due to economy of scales when compared to centralized building units, and the existing framework conditions have favorable aspects that could make such an implementation thrive. That notwithstanding, several barriers do exist both at an institutional level and in practical terms, that may not yet allow for such an initiative to take hold, or be a compelling case for local actors.

Expanding upon this, the following conclusions were drawn in relation to the subquestions first presented in Section 1.4:

- Climate change, energy efficiency and sustainable construction policy may serve as platforms for the introduction of district cooling in Lima, and an initial implementation with public institutions may be the path of least resistance for such a project.
- The financial metropolitan commercial zone and the special regulatory zone of the San Isidro district have high cooling demand densities and a critical mass of building that could benefit from connecting to a district cooling system.
- The deployment of a district cooling system should be conducted as a phased approach, and should consider a configuration with electric chillers and storage as main components of the system to allow for better operations during peak hours, as well as lower system costs. Free cooling should be further investigated for implementations in closer proximity to the sea.

- District cooling can be a cost effective alternative, when compared to conventional onsite cooling solutions, and provide savings in term of investment and energy costs for cooling.
- Policy suggestions that enhance the prospects of district cooling include working under the existing policy framework and institutional initiatives, using energy mapping as a tool for identifying new district cooling potential, and promoting the benefits of district cooling among institutions and society.

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A

Additional Tables

A.1 Sample Cashflow Tables

Tab. A.1.: Sample cashflow calculations for the Electric Chiller with Partial TES, Ref. configuration in Site A.

	Phase 1:	4,887.47 MWh, cooling load serve				Phase 2:	19,499.11 MWh, cooling load serve			
Year	0	1	2	3	4	5	6	7	8	9
Capital Expenditures										
Plant										
Chiller	-$ 101,500.57	$ -	$ -	$ -	$ -	-$ 288,944.79	$ -	$ -	$ -	$ -
Cooling Towers	-$ 290,817.93	$ -	$ -	$ -	$ -	-$ 827,880.32	$ -	$ -	$ -	$ -
Cold Storage	-$ 552,420.24	$ -	$ -	$ -	$ -	-$ 1,572,591.63	$ -	$ -	$ -	$ -
Auxiliaries, Electric & Building	-$ 643,119.87	$ -	$ -	$ -	$ -	-$ 1,840,538.10				
Distribution Network										
Piping	-$ 922,689.51	$ -	$ -	$ -	$ -	-$ 1,022,287.31	$ -	$ -	$ -	$ -
Pumps	-$ 7,744.56	$ -	$ -	$ -	$ -	-$ 12,297.63	$ -	$ -	$ -	$ -
Contingency	-$ 187,517.28	$ -	$ -	$ -	$ -	-$ 372,400.17	$ -	$ -	$ -	$ -
Operational Expenditures										
Plant										
Energy Cons., Chiller		-$ 59,022.49	-$ 59,022.49	-$ 59,022.49	-$ 59,022.49	-$ 235,477.10	-$ 235,477.10	-$ 235,477.10	-$ 235,477.10	-$ 235,477.10
Energy Cons., Auxiliaries		-$ 23.90	-$ 23.90	-$ 23.90	-$ 23.90	-$ 91.93	-$ 91.93	-$ 91.93	-$ 91.93	-$ 91.93
Maintenance		-$ 3,700.00	-$ 3,700.00	-$ 3,700.00	-$ 3,700.00	-$ 7,400.00	-$ 7,400.00	-$ 7,400.00	-$ 7,400.00	-$ 7,400.00
Water Cost		-$ 4,261.350	-$ 4,261.35	-$ 4,261.35	-$ 4,261.35	-$ 16,392.26	-$ 16,392.26	-$ 16,392.26	-$ 16,392.26	-$ 16,392.26
Distribution Network										
Piping, O&M		-$ 4,613.45	-$ 4,613.45	-$ 4,613.45	-$ 4,613.45	-$ 5,111.44	-$ 5,111.44	-$ 5,111.44	-$ 5,111.44	-$ 5,111.44
Pumping Power Costs		-$ 10,705.23	-$ 10,705.23	-$ 10,705.23	-$ 10,705.23	-$ 41,180.12	-$ 41,180.12	-$ 41,180.12	-$ 41,180.12	-$ 41,180.12
Pumping, Maintenance		-$ 232.34	-$ 232.34	-$ 232.34	-$ 232.34	-$ 601.27	-$ 601.27	-$ 601.27	-$ 601.27	-$ 601.27
Water Cost		-$ 276.23	-$ 276.23	-$ 276.23	-$ 276.23	-$ 838.92	-$ 838.92	-$ 838.92	-$ 838.92	-$ 838.92
Revenue										
Cooling sales		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Salvage value		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Net Annual Cashflow	-$ 2,705,809.96	-$ 82,834.98	-$ 82,834.98	-$ 82,834.98	-$ 82,834.98	-$ 6,244,032.99	-$ 307,093.04	-$ 307,093.04	-$ 307,093.04	-$ 307,093.04
Discounted CAPEX	-$ 2,705,809.96	$ -	$ -	$ -	$ -	-$ 4,879,731.87	$ -	$ -	$ -	$ -
Discounted OPEX	-$ 82,834.98	-$ 79,649.02	-$ 76,585.60	-$ 73,640.00	-$ 70,807.69	-$ 252,408.10	-$ 242,700.09	-$ 233,365.47	-$ 224,389.88	-$ 215,759.50
Total Discounted Cashflow	-$ 2,705,809.96	-$ 79,649.02	-$ 76,585.60	-$ 73,640.00	-$ 70,807.69	-$ 5,132,139.97	-$ 242,700.09	-$ 233,365.47	-$ 224,389.88	-$ 215,759.50
Cumulative DCF	-$ 2,705,809.96	-$ 2,785,458.99	-$ 2,862,044.58	-$ 2,935,684.58	-$ 3,006,492.27	-$ 8,138,632.24	-$ 8,381,332.33	-$ 8,614,697.80	-$ 8,839,087.68	-$ 9,054,847.18

Total Project NPV	-$21,094,120.03	-$ 21,094,120.03			
Total CAPEX@4%	-$ 13,376,729.40		**Discount Rate**	4.0%	
Total OPEX@4%	-$ 7,800,225.61		**Yearly Cold Sales**	$ -	USD/MWh
Levelized Cost	43.89547	USD/MWh			

Tab. A.2.: Continuation of cashflow calculations for the Electric Chiller with Partial TES, Ref. configuration in Site A.

Year/Phases										
Phase 3:	45,391.31 MWh, cooling load serve				Phase 4:	81,472.99 MWh, cooling load serve				
10	11	12	13	14	15	16	17	18	19	20
-$ 688,859.38	$ -	$ -	$ -	$ -	-$ 1,061,696.11	$ -	$ -	$ -	$ -	$ -
-$ 1,338,948.79	$ -	$ -	$ -	$ -	-$ 2,063,638.46	$ -	$ -	$ -	$ -	$ -
-$ 2,543,386.53	$ -	$ -	$ -	$ -	-$ 3,919,963.43	$ -	$ -	$ -	$ -	$ -
-$ 2,976,514.33					-$ 4,588,679.83					
-$ 954,832.40	$ -	$ -	$ -	$ -	-$ 1,488,213.71	$ -	$ -	$ -	$ -	$ -
-$ 20,117.05	$ -	$ -	$ -	$ -	-$ 29,841.68	$ -	$ -	$ -	$ -	$ -
-$ 554,614.41	$ -	$ -	$ -	$ -	-$ 856,335.34	$ -	$ -	$ -	$ -	$ -
-$ 548,159.04	-$ 548,159.04	-$ 548,159.04	-$ 548,159.04	-$ 548,159.04	-$ 983,892.12	-$ 983,892.12	-$ 983,892.12	-$ 983,892.12	-$ 983,892.12	-$ 983,892.12
-$ 201.95	-$ 201.95	-$ 201.95	-$ 201.95	-$ 201.95	-$ 371.53					
-$ 4,350.00	-$ 4,350.00	-$ 4,350.00	-$ 4,350.00	-$ 4,350.00	-$ 13,050.00	-$ 13,050.00	-$ 13,050.00	-$ 13,050.00	-$ 13,050.00	-$ 13,050.00
-$ 36,011.85	-$ 36,011.85	-$ 36,011.85	-$ 36,011.85	-$ 36,011.85	-$ 178,636.21	-$ 178,636.21	-$ 178,636.21	-$ 178,636.21	-$ 178,636.21	-$ 178,636.21
-$ 4,774.16	-$ 4,774.16	-$ 4,774.16	-$ 4,774.16	-$ 4,774.16	-$ 7,441.07	-$ 7,441.07	-$ 7,441.07	-$ 7,441.07	-$ 7,441.07	-$ 7,441.07
-$ 90,467.83	-$ 90,467.83	-$ 90,467.83	-$ 90,467.83	-$ 90,467.83	-$ 166,431.90	-$ 166,431.90	-$ 166,431.90	-$ 166,431.90	-$ 166,431.90	-$ 166,431.90
-$ 1,204.78	-$ 1,204.78	-$ 1,204.78	-$ 1,204.78	-$ 1,204.78	-$ 2,100.03	-$ 2,100.03	-$ 2,100.03	-$ 2,100.03	-$ 2,100.03	-$ 2,100.03
-$ 1,652.47	-$ 1,652.47	-$ 1,652.47	-$ 1,652.47	-$ 1,652.47	-$ 2,716.05	-$ 2,716.05	-$ 2,716.05	-$ 2,716.05	-$ 2,716.05	-$ 2,716.05
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$17,790,698.46
-$ 9,764,094.96	-$ 686,822.08	-$ 686,822.08	-$ 686,822.08	-$ 686,822.08	-$ 15,363,007.46	-$ 1,354,267.39	-$ 1,354,267.39	-$ 1,354,267.39	-$ 1,354,267.39	$ 16,436,431.08
-$ 6,132,280.31	$ -	$ -	$ -	$ -	-$ 7,778,349.79	$ -	$ -	$ -	$ -	$ 8,119,442.54
-$ 463,992.39	-$ 446,146.53	-$ 428,987.04	-$ 412,487.54	-$ 396,622.64	-$ 752,182.90	-$ 723,054.43	-$ 695,244.64	-$ 668,504.46	-$ 642,792.75	-$ 618,069.96
-$ 6,596,272.70	-$ 446,146.53	-$ 428,987.04	-$ 412,487.54	-$ 396,622.64	-$ 8,530,532.70	-$ 723,054.43	-$ 695,244.64	-$ 668,504.46	-$ 642,792.75	$ 7,501,372.59
-$ 15,651,119.88	-$ 16,097,266.40	-$ 16,526,253.45	-$ 16,938,740.99	-$ 17,335,363.63	-$ 25,865,896.32	-$ 26,588,950.75	-$ 27,284,195.39	-$ 27,952,699.86	-$ 28,595,492.61	-$ 21,094,120.03

A.2 Sensitivity Tables

Tab. A.3.: Continuation of cashflow calculations for the Electric Chiller with Partial TES, Ref. configuration in Site A.

Sensitivity Variation	Chiller Plant, +/-10%	Cold Storage, +/-10%	Dist. Network, +/-10%	Energy Price, +/-10%	O&M, +/-10%	Contingency, +/-5%	Salvage Value, +/-2.5%	Discount Rate, +/-2%
	NPCs with deviations from base scenario							
+	19,981,097	20,520,139	20,754,930	20,415,426	21,000,937	20,422,233	21,237,844	24,076,277
Base	21,094,120	21,094,120	21,081,948	21,094,120	21,093,968	21,094,120	21,094,120	21,094,120
-	22,207,143	21,668,101	21,408,966	21,772,814	21,186,998	21,766,007	20,950,396	18,478,641
	LCOCs with deviations from base scenario							
+	41.58	42.70	43.19	42.48	43.70	42.50	44.19	50.10
Base	43.90	43.90	43.87	43.90	43.90	43.90	43.90	43.90
-	46.21	45.09	44.55	45.31	44.09	45.29	43.60	38.45
	Percent variation from base scenario							
+	-5.28%	-2.72%	-1.55%	-3.22%	-0.44%	-3.19%	0.68%	14.14%
Base	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
-	5.28%	2.72%	1.55%	3.22%	0.44%	3.19%	-0.68%	-12.40%

Tab. A.4.: Continuation of cashflow calculations for the Electric Chiller with Partial TES, Ref. configuration in Site A.

Sensitivity Variation	Chiller Plant, +/-10%	Cold Storage, +/-10%	Dist. Network, +/-10%	Energy Price, +/-10%	O&M, +/-10%	Contingency, +/-5%	Salvage Value, +/-2.5%	Discount Rate, +/-2%
	NPCs with deviations from base scenario							
+	16,919,870	14,021,027	13,563,626	10,703,185	11,531,703	10,740,466	11,132,397	11,716,126
Base	18,032,893	14,595,009	13,890,644	11,058,414	11,624,733	11,058,414	11,058,414	11,058,414
-	19,145,917	15,168,990	14,217,662	11,413,644	11,717,763	11,376,363	10,984,432	10,539,472
	LCOCs with deviations from base scenario							
+	58.94	48.84	47.25	37.28	40.17	37.41	38.78	40.81
Base	62.81	50.84	48.39	38.52	40.49	38.52	38.52	38.52
-	66.69	52.84	49.52	39.76	40.82	39.63	38.26	36.71
	Percent variation from base scenario							
+	-6.17%	-3.93%	-2.35%	-3.21%	-0.80%	-2.88%	0.67%	5.95%
Base	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
-	6.17%	3.93%	2.35%	3.21%	0.80%	2.88%	-0.67%	-4.69%