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Scaling Sustainable Infrastructure: District Design for the Triple Bottom Line

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Scaling Sustainable Infrastructure: District Design for the Triple Bottom Line

by

Anika Hall

An undergraduate honors thesis submitted in partial fulfillment of the

requirements for the degree of

Bachelor of Science

in

University Honors

and

Civil Engineering

Thesis Adviser

Corey Griffin

Portland State University

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Abstract

Multiple forms of infrastructure are required to make anywhere habitable by modern standards. These systems include black and gray water treatment, stormwater management, electricity generation, cooling/heating systems, and amenities. There are multiple methods to address all these systems, and each is optimized at a different scale. As urban populations rise, and resources become limited, cities are being pushed to grow in creative and sustainable ways. This requires consideration of the social, economic and environmental sustainability of the growth strategies chosen. To do this properly, strategies to address each required infrastructure system must be analyzed, considering their pros and cons with regards to each sustainability type, and the proper scale at which it should be implemented. This thesis utilizes literature review, professional interviews, and physical site visitations to do this type of analysis. From this, an example district retrofit strategy was created for Hassalo on 8th, one of the observed sites. Many infrastructure systems can be strategically combined to create highly efficient districts. In the United States, there are ownership, policy and social barriers preventing the implementation of these strategies. This thesis presents a qualitative analysis of each infrastructure strategy, but the data necessary to create a quantitative comparison is lacking. To overcome these barriers, further research into methods employed in other countries still needs to be done.

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Finally, thank you to Pandora Patterson of Kailash Village and Joanna Tran of Catholic Charities Oregon for describing the systems used in their communities. Exposure to a diversity of district designs has helped me to understand the full scope of communities that they can support. Your time is appreciated.

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Introduction

District design is an urban planning process through which multiple blocks are designed as an integrated system. At a larger scale, Ecodistrict design is defined as the creation of “an integrated and resilient district or series of neighborhoods that is resource efficient; that captures, manages, and reuses a majority of energy, water and waste onsite; is home to a range of transportation options; provides a rich diversity of habitat and open space; and enhances community engagement and wellbeing” (Monroe, 2012). Currently, the infrastructure systems supporting our cities are designed in a patchwork: waste treatment, water distribution, electrical supply, heating and cooling systems, transportation pathways. Traditionally, each infrastructure type has been designed in isolation, but the pressing issues (population growth, climate change, etc.) our cities are beginning to face call for a stronger, more integrated, and resilient method of design.

As more than half of the world’s population resides in urban centers, and the number continues to grow, trends project that urban land will triple by 2030. This growth has brought about discussions of how to best develop our cities in a sustainable manner (Luederitz et. al, 2013). Increased urbanization comes at a time where societies globally better understand the challenges of increasingly limited resources and climate change caused by greenhouse gas emissions. These challenges require cities to accommodate such growth and increasing demand on current infrastructure systems with broader and more creative strategies.

It is the duty of civil engineers to participate in this process. The 1st Canon of the American Society of Civil Engineers (ASCE) Code of Ethics states that “(e)ngineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties”. This is further expanded on in part a of Canon 1 with the declaration that “(e)ngineers shall recognize that the lives, safety, health and welfare of the general public are dependent upon engineering judgments, decisions and practices incorporated into structures, machines, products, processes and devices.” (ASCE, 2017).

In the current conditions that our society faces, this section of the ASCE Code of Ethics holds civil engineers to expand their circle of influence to interact with and understand principles from other disciplines, such as architecture and urban planning. The urgent need for creative development requires cross-disciplinary thinking. Proper strategic district design requires collaboration from all fields. As the designers of infrastructure systems, it is the ethical responsibility of civil engineers to strive to better understand the proper scale at which to implement these systems, and the pros and cons of combining them together in a holistic manner.

When analyzing any design project for sustainability, there are three parameters to consider: the environmental, the social and the economic sustainability – often called the triple bottom line. By consciously reducing resource consumption and pollutant emissions, a development can optimize its environmental sustainability. By bolstering community interaction, increasing perceived quality of life, and providing accessible space for a variety of interests, a development can optimize its social sustainability. By assuring equitable access to all socio-economic groups and assuring an affordable budget throughout the lifespan of the project, a development can optimize its economic sustainability. These strategies are examples among many. However, all three aspects of the triple bottom line must be considered for a development to truly be considered sustainable.

Many researchers, designers and planners have argued that the ideal scale for sustainable development is the “district scale”, as it is large enough to support independent infrastructure systems, but small

enough to be managed as one project with an agreed upon set of goals. It appears to be the only scale at which all three components of sustainability can truly be implemented, well managed and accurately measured (Monroe, 2012). Each infrastructure type is optimized at different sizes, and proper understanding of these differences and similarities can allow for integration and interaction of these systems together.

Decentralized infrastructure systems add to the resiliency of city planning. If only one centralized service exists for a city, such as one electrical production or waste treatment facility, the city is much more vulnerable in the occurrence of a natural disaster. If that one facility breaks, it leaves the entire city without access to electricity or waste treatment until it is fixed. If there are multiple systems distributed throughout the city, there are more possibilities of system survival in an emergency. As the rate of natural disasters increase globally (see Figure 1) the chances of a city experiencing a natural disaster also increases. Decentralized infrastructure can help cities to prepare and adapt, becoming more resilient in a changing climate.

Figure 1: Number of natural disasters experienced globally by year. (The Economist, 2017)

The purpose of this thesis is to analyze the different strategies available in district-scale infrastructure design. It aims to consider for each the proper scale at which they should be implemented and their pros and cons with regards to the three components of sustainability. According to a study done by Christopher Luederitz, Daniel Lang, and Henrik Von Wehrden, there is currently very little research published about district design techniques (Luederitz et al., 2013). This needs to change. Through literature review, physical site visitation and interviews with relevant professionals, this thesis aims to put together a guide for relative comparison of various infrastructure systems as they can be applied in district design and retrofit of existing buildings.

Methods

In the beginning, research for this thesis was conducted through extensive literature review. The original plan and goal was to gather statistics, through case studies and design guides, on the efficiency of a variety of centralized infrastructure types and their proper scale. From there, a quantitative table was to be made analyzing the proper size, cost, embodied carbon, and emissions for each system. As the beginnings of this research grew, it became apparent that there is currently very little written about this topic. Due to both time constraints and the available literature, the desired comparison was unattainable. This led to a change in research methods, incorporating interviews with relevant professionals, physical site tours, and further investigation into case studies.

A list of the relevant professionals interviewed can be found in Appendix A. These professionals included four experienced architects and urban planners, one district resident, five district workers, and two district managers. Architects are responsible for systems integration into any district design. District workers and managers understand the technicalities behind running a district business or working within one. District residents and workers can speak to the experience of residing within a district.

The cases studied in this thesis present a wide range of district infrastructure examples. Because of this, analyzing many case studies was an integral step in the research to allow for proper comparison of these systems. A detailed list of the sites toured as well as additional sites studied through literature review is presented below. These sites were studied as examples of district design.

The information gathered through these means was used in lieu of quantitative data in this thesis and broken into two sections. Information gathered including implementation strategies and social sustainability considerations, was analyzed and considered to be “Non-technical Data”. Each infrastructure type studied during the research portion of this thesis was dissected and analyzed for its pros and cons in reference to the triple bottom line of sustainability. This section was considered to be “Technical Data”. Knowledge from both of these sections was then used to create an example retrofit strategy for one of the sites toured, incorporating considerations learned in each.

Nontechnical Data

Sites Toured

Portland State University Campus

General: The Portland State University (PSU) campus is located in downtown Portland, Oregon. Because of its location, many parts of the campus blend in with the surrounding city infrastructure. As a university, PSU has many goals to achieve a more sustainable campus. As part of this effort, the campus has worked to install an extensive stormwater treatment system, as well as a district wide heating and cooling energy loop, called the “Campus Loop”. Some of the newer buildings on campus were installed with systems in place to reuse gray and stormwater for non-potable uses, such as the flushing of toilets and irrigation. These systems are currently all installed individually per building, however, and do not utilize full district design principles in the same way that the Campus Loop does.

*It should be noted that PSU is often referred to as a commuter school. Many of the people counted in this population are not full-time residents of the campus, and therefore the calculated density may be exaggerated compared to what the system experiences on a daily basis.

Figure 2: Map of the Portland State University (PSU) campus. (Mobile Maplets, 2014)

Size:	49 acres	Population:	~30,000	Density:	~612 people/acre
Electrical Supply:	City				
Cooling/Heating System:	Campus energy loop				
Black Water Treatment:	City				
Gray Water Treatment:	City; Non-potable reuse				
Stormwater Management:	City; Bioswales; Green roof; Non-potable reuse				
Centralized Amenities:	Parks; Cultural/community centers; Recreation center; Food pantry; Share shelves				
Combined Systems:	None				

Table 1: Infrastructural breakdown of the Portland State University campus.

Electrical Supply: Standard as provided by the city.

Cooling/Heating System: The PSU campus is connected through the “Campus Loop”, “a district energy system that provides heating and cooling to multiple buildings in the core of campus. Centralized locations generate steam and chilled water which are distributed through a network of pipes to connected buildings. As a result, each building does not require individual boilers and chillers.” (Portland State University, n.d.)

Black Water Treatment: Standard as provided by the city.

Gray Water Treatment: Most of the PSU campus sends its gray water to the city for standard treatment. A few newer buildings on the campus are designed to reuse their gray water for non-potable necessities, such as flushing of toilets, but this is not standard across the campus.

Stormwater Management: Stormwater management across the campus is treated primarily through the installation of raingardens and bioswales as well as roughly eight blocks of open park space. A few newer buildings on campus capture rainwater through a cistern system for non-potable reuse and irrigation. What is not treated in this manner drains into the city stormwater system.

Centralized Amenities: As a university, PSU provides many amenities to its students. These include a centralized clinic, cultural and community centers, a centralized plaza and recreational center, a food pantry, and a supply share room to name a few. This is common place for most campuses, as they aim to provide a centralized location to meet all of their students’ residential and academic needs.

Combined Systems: None

Kailash Ecovillage

General: Kailash Ecovillage is a repurposed neglected apartment building in Portland Oregon. The site also contains one building that meets the Passivhaus standard with space for 5 units. Kailash was founded by a group of real-estate developers who wanted to see more integrated cohousing models adopted in the US. The site is run as a business, with each apartment room leased out by the owners to individuals at a market rate determined at the time a new contract is signed. This means that rental rates are not often raised, each individual pays the specific market rate from their move in date. An elected panel of residents help to make decisions regarding the entire community, with the business owners ultimately having the final decision.

According to their website, they are a “community committed to providing a sustainable, beautiful, and safe living environment for individual residents as well as the greater community”. Their commitment to community involvement pushes them to constantly evolve, testing social, economic and environmental sustainability strategies that many other district designs studied in this thesis were not capable of testing.

Figure 3: Aerial view of Kailash Ecovillage (Kailash, 2017)

Size:	2 acres	Population:	~60	Density:	~30 people/acre
Electrical Supply:	City power grid; Solar				
Cooling/Heating System:	5 passivehaus units; Solar showers; City powered HVAC				
Black Water Treatment:	City sewage; Humanure composting system; Urine fertilization system				
Gray Water Treatment:	Irrigation; City				
Stormwater Management:	Rainwater harvesting; Bioswales and rain gardens; Irrigation; Retention pond				
Centralized Amenities:	Community room; Laundry; Mail; Garden; Vehicle, bike and tool share; Food and share shelves				
Combined Systems:	None				

Table 2: Infrastructural breakdown of Kailash Ecovillage.

Electrical Supply: Most of the electricity at Kailash is provided through the standard city electrical grid, with roughly 5% of their needs met by onsite solar. Due to density constraints, Kailash is unable to provide the amount of power that they need onsite through solar. The demand is too high to be met by the amount of available area.

Cooling/Heating System: Majority of the heating and cooling needs at Kailash are met electrically through HVAC systems powered through standard city electricity. The passivehaus building onsite was intentionally built to reduce the necessary heating as much as possible. Most of the heating needs for this building are met passively through solar heating. Kailash has also built two solar showers and a solar sink. Though these systems are not large enough to adequately serve all of the community's needs, they work to reduce the community's reliance on exterior power sources.

Black Water Treatment: Most black water at Kailash is treated through the standard city sewer system. However, the site is also home to an humanure composting system as well as a urination station fertilizer system. Not all the residents participate in these alternative waste treatment systems, but they are sized to serve the entire community if necessary.

Gray Water Treatment: Most of the gray water at Kailash is treated through the standard city sewer system. However, all of the gray water produced from the solar showers and solar sink is filtered and distributed as irrigation into the community garden as non-potable reuse.

Stormwater Management: All of the stormwater at Kailash is treated onsite. A 1,500 gallon cistern collects rain water to provide emergency water supply onsite. What is not collected is treated through an elaborate system of rain gardens, bioswales and garden irrigation draining into a retention pond in case of flood events.

Centralized Amenities: Kailash works extensively to provide its residents with a sense of community through its centralized and shared amenities. These include shared laundry, mail, and community gathering space, as well as a playground for children, a vehicle and tool sharing system, a "free room" where residents can leave donations for others in the community, and $\frac{3}{4}$ acres of shared and private gardening space. Residents can host workshop days or provide a meal train system where each person takes a turn cooking dinner for others of the community in need, but participation is not mandatory.

Though these centralized amenities work to build a strong community, residents of Kailash are generally autonomous and do not consider the community to be cohousing or a commune.

Combined Systems: The reuse of gray water and stormwater for food irrigation as well as treated waste for fertilizer is the only combined system within Kailash.

Brewery Blocks

General: The Brewery Blocks are a five-block system in the Pearl district of Portland, Oregon. These blocks are comprised primarily of high-end residential and commercial spaces. Most of the Brewery Blocks was designed originally as a system, with two historical buildings retrofit to be connected in through a massive chiller loop and underground parking system which spans most of the five blocks of the district. The retrofit buildings in the district were renovated as part of the development process. These renovations provided opportunity for both seismic and energy retrofits, improving both the safety and energy efficiency of the connected buildings. This process was spurred by the mayor of Portland at the time who desired to connect the Pearl district to Portland's adjacent downtown. Portland Energy Solutions, who was already working to provide power to the district, worked to install a massive chiller sized to serve 1/3 of the downtown Portland area. Currently, this chiller is running at about 10% capacity to serve the Brewery Blocks. The amount of infrastructure installation necessary to expand this scope has unfortunately limited any further progress in connecting the rest of downtown Portland to this cooling system.

Figure 4: Map of the Brewery Blocks (Brewery Blocks, n.d.)

Size:	5 blocks	Population:	~2000	Density:	~436 people/acre
Electrical Supply:	City; Solar				
Cooling/Heating System:	Chiller loop				
Black Water Treatment:	City				
Gray Water Treatment:	City				
Stormwater Management:	Massive manhole filtration				
Centralized Amenities:	Parking				
Combined Systems:	None				

Table 3: Infrastructural breakdown of the Brewery Blocks.

Electrical Supply: Standard as provided by the city, with solar supplementation.

Cooling/Heating System: As most of the Brewery Blocks are densely populated commercial spaces, the issues these buildings tend to face are with over-heating rather than heating demand. The massive chiller system provides cool water that is run through pipes throughout the district where it removes heat from the buildings. The water within the system is recycled through the chiller in a continuous cycle.

Black Water Treatment: Standard as provided by the city.

Gray Water Treatment: Standard as provided by the city.

Stormwater Management: The stormwater produced by the highly nonpermeable landscape of the Brewery Blocks is treated through an underground filtration system stored within the manholes onsite. This water is then repurposed for toilet flushing at one building, irrigate onsite landscaping, and allowed to trickle back into the local watershed.

Centralized Amenities: Three blocks of underground parking span the Brewery Blocks, including bike storage and showering facilities. This provides the necessary parking for its densely populated and highly trafficked location in Portland's Pearl district. This has also worked to provide the necessary space to install the complex piping network needed for the district wide chiller loop.

Combined Systems: None.

Hassalo on 8th

General: Hassalo on 8th is a high-end redevelopment master planning project in the Lloyd district of Portland, Oregon. The project development involved the conversion of four blocks of parking space into 22 stories of luxury, LEED Platinum-certified apartments, and the renovation of 16 stories of office and retail space. The four blocks were designed to be pedestrian focused, providing an attractive walkable corridor and plaza for spatial connection. The highlight of the project is the onsite wastewater treatment plant, or NORM (Natural Organic Recycling Machine). This system treats 100% of the black and gray water produced by the new buildings and repurposes it for use in cooling, irrigation, and the toilets. 100% of the stormwater produced onsite is also treated through a series of rain gardens, bioswales and green roofs. Underground parking connects the district and provides both bike parking and repair services.

Figure 5: Digital rendering of Hassalo on 8th, per GBD architects (Winter, n.d.).

Size:	4 blocks	Population:	~600	Density:	~165 people/acre
Electrical Supply:	City				
Cooling/Heating System:	Repurposed water loop				
Black Water Treatment:	NORM; City				
Gray Water Treatment:	NORM; City				
Stormwater Management:	Raingardens and bioswales; Green roofs				
Centralized Amenities:	Community rooms; Plaza; Recreation center				
Combined Systems:	NORM, heat and non-potable water reuse				

Table 4: Infrastructural breakdown of Hassalo on 8th.

Electrical Supply: Standard as provided by the city.

Cooling/Heating System: Combined into NORM for the new buildings using a heat exchange water loop. Standard as provided by the city for the retrofit office building.

Black Water Treatment: Combined into NORM for the new buildings. Standard as provided by the city for the retrofit office building.

Gray Water Treatment: Combined into NORM for the new buildings. Standard as provided by the city for the retrofit office building.

Stormwater Management: 100% of the stormwater produced onsite is treated through a system of green roofs, raingardens and bioswales.

Centralized Amenities: Hassalo on 8th is comprised of individual luxury apartments, office space and retail space. Residents and workers tend to operate very independently, but the design does make effort to offer certain space encouraging social interaction between residents. These include a centralized plaza in a highly walkable setting, which encourages office workers and residents alike to

spend time in the sunshine during their down time. Community spaces provided in each apartment complex as well as a recreational area offer residents some spaces to meet and interact with one another on a regular basis.

Combined Systems: Hassalo on 8th is home to an innovative example of combined infrastructure: NORM. Standing for “Natural Organic Recycling Machine”, NORM is one of the first district-scale, decentralized, urban wastewater treatment and reuse systems in the United States. The system treats 100% of the wastewater (both black and gray) produced by the three new buildings onsite. The treated water is used to meet 100% of the non-potable water demands for the three new buildings. This includes providing water to flush toilets, irrigate plants, and provide cooling services to the buildings onsite. What treated water is not reused is either held onsite in storage for drier seasons or allowed to return to the local watershed.

Additional Sites Researched

Kenton Women’s Village

General: The Kenton Women’s Village is a limited duration pilot project in the Kenton neighborhood of Portland, Oregon. This project provides micro-housing sleeping pods for up to 14 homeless women. This is done in a village-style community overseen and supported by Catholic Charities, a contracted non-profit. The sleeping pods are provided donations from local architecture firms in Portland. The sleeping pods provided are unheated but are designed to be no larger than 4’x8’, small enough to heat with personal body heat. The individual pods have no electricity or running water. Black and gray water are collected and trucked off site on a weekly basis, as no permanent utilities are in place. The site is completely paved and has no way of addressing stormwater onsite. The purpose of the site is to provide a safe space for the women to sleep and store their items during the day while they seek permanent housing. Due to its ephemeral nature, the site has no permanent infrastructure, only mobile units. It is instead built permissibly on an abandoned city lot.

A centralized community space provides a kitchen and bathroom facility, donation shed (for things such as hygiene items and winter clothing), and a heated community space. By providing a safe and stable place to sleep, the Kenton Women’s Village allows its residents better sleep and less stress, thus improving their health and giving them the energy that they need to find employment and permanent residents. The social structure provided through the village model keeps the residents accountable to one another, and is extremely important, as homelessness can often be very isolating. All residents of the village are required to actively be pursuing employment and permanent housing in order to remain and stay on the site. The site is unable to provide case management services, as Catholic Charities is not equipped to handle such a task on top of running the site and providing a place of temporary residence. This district model is a practical, easily adoptable method to temporarily alleviate the burden of homelessness, allowing residents the energy necessary to find permanent housing and employment. The social services necessary to aid on these steps however are not included on the project site.

Figure 6: Aerial view of the Kenton Women's Village per Zach Putnam (Patail, 2017).

Size:	1 acre	Population:	14	Density:	14 people/acre
Electrical Supply:	City				
Cooling/Heating System:	Body heat; Propane				
Black Water Treatment:	Trucked offsite				
Gray Water Treatment:	Trucked offsite				
Stormwater Management:	City				
Centralized Amenities:	Kitchen; Restroom; Heated community space; Donation shed				
Combined Systems:	None				

Table 5: Infrastructural breakdown of Kenton Women's Village

Electrical Supply: Electricity onsite is provided by the city for cooking.

Cooling/Heating System: Individual units are small enough to be heated with body heat. The community space is heated by propane lamps.

Black Water Treatment: The black water produced at the Kenton Women's Village is collected weekly to be treated offsite.

Gray Water Treatment: The gray water produced onsite is collected weekly with the black water and treated offsite.

Stormwater Management: Standard as provided by the city.

Centralized Amenities: The centralized amenities at the Kenton Women's Village are the most notable of the district design strategies. The kitchen, restroom and centralized community space allows each of its residents to care for their needs and build social connections. A donation shed provides village residents with basic items they may not otherwise have access to.

Combined Systems: None

Going Street Commons

General: Going Street Commons is a master planned future development in the Cully neighborhood of Portland, Oregon. The project aims to convert a residential city lot into a net zero sustainably conscious community. The community is designed for aging in place, while simultaneously providing playground access for younger children. It consists of 13 passivehaus units, each designed to be highly energy efficient. The development faced financial difficulties due to interest associated with required loans and building fees associated with rezoning. This combined with density restrictions due to zoning forced the developer to sell each unit at market rate, limiting the access for low income individuals, stifling the initial diversity goals of the project.

The district was designed by Birdsmouth Construction, a master planning architecture firm. Power dynamics were considered during the district design. Written into the contract of the individual units sold is the consideration that owners of each unit will form a comity to make decisions governing the district as a whole. Solar power is distributed among the units, as some produce more than others due to shading. Tool and garden sharing are encouraged, but no centralized community building exists.

A PORTLAND COMMUNITY; INSPIRED, DESIGNED AND BUILT FOR A ZERO ENERGY FUTURE

Figure 7: Site design of the Going Street Commons (Birdsmouth Construction, n.d.).

Size:	1.3 acres	Population:	~33	Density:	~25 people/acre
Electrical Supply:	Solar				
Cooling/Heating System:	Passivehaus; Electrical				
Black Water Treatment:	City				
Gray Water Treatment:	Irrigation				
Stormwater Management:	Rain garden; Yard space				
Centralized Amenities:	Community garden; Mail room; Strategic edibles				
Combined Systems:	None				

Table 6: Infrastructural breakdown of Going Street Commons.

Electrical Supply: 100% of the electrical needs onsite are met with a net metering solar system. Energy is sold to the city grid when excess is provided and rebought back during seasonal periods where the sun does not shine enough to meet the community's needs.

Cooling/Heating System: Each unit is designed to meet the Passivehaus standard, and therefore requires very little energy to maintain a comfortable temperature. What heating and cooling needs are not met by the passive processes are optionally accounted for through electrical heating supply.

Black Water Treatment: Standard as provided by the city.

Gray Water Treatment: Gray water is collected for reuse in irrigation for the lawn and garden areas.

Stormwater Management: Stormwater runoff is collected and used for irrigation in the lawn and garden areas.

Centralized Amenities: One of the goals of the Going Street Commons project was to show that a net zero community can be as comfortable and standard as a typical market rate house. Because of this, each unit is equipped with 100% of the amenities typical of a market rate house. To create a sense of community the development employs the use of a centralized garden and mail room. It also strategically places edible plants between neighboring houses to encourage residents to slow down and interact with one another.

Combined Systems: None

Vauban

General: Vauban is a community in Freiburg, Germany. The site is built on a repurposed military base, with development lead by a community association (Forum Vauban) "contracted by the city to lead residents 'participation, the elaboration of sustainability goals and public relations work'". The site was developed in multiple stages: Barrack conversion by a student village and alternative housing group; construction of new, energy efficient residential buildings throughout the site; construction of a 'solar village'; and finally the integration of commercial/light industrial uses into the northern residential section. Many of the newly constructed units meet passivehaus standard, with solar supported heating systems as well as intelligent ventilation with heat-recapture devices. Originally built using traditional city infrastructure to treat black and gray water, the district has implemented a vacuum converter onsite to treat majority of the sewage and organic waste, producing and capturing biogas in the process. Most of the stormwater produced onsite is collected and repurposed for applications such as toilet and garden water. (Scheurer and Newman, 2009).

Most of the individual residential blocks designed during the second stage “were sold to small cooperatives of owner-occupiers, each comprising between 3 and 21 households (Baugruppen)”. These individual groups were responsible for the detailed building design of their shared property, resulting in a wide diversity within the district. These smaller, self-driven projects allowed for a stronger focus on social and economic sustainability goals than is often achievable in large district scale projects. Rental housing, including share-owned self-governed rental housing, is present within the community as well for residents lacking the funds to own houses. Throughout the district, there is strong social education in place about topics such as individual waste reduction and proper recycling. Extensive walkable greenspaces coupled with separately parking spaces sold at high rates incentivize residents to rely on alternative forms of transportation or car sharing (Nobis, 1999).

Figure 8: Map of Vauban (Monroe, 2012).

Size:	84 acres	Population:	~5,500	Density:	~65 people/acre
Electrical Supply:	Solar				
Cooling/Heating System:	Passive; Heat recovery ventilation; Electrical				
Black Water Treatment:	City; Vacuum converter				
Gray Water Treatment:	City; Non-potable reuse				
Stormwater Management:	Collection; Non-potable reuse				
Centralized Amenities:	Car share				
Combined Systems:	Vacuum converter: Biogas from sewage and organic waste				

Table 7: Infrastructural breakdown of Vauban.

Electrical Supply: Vauban has two main energy sources within the district. These include a distributed system of solar panels as well as the employed use of biogas collected from the onsite waste treatment.

Cooling/Heating System: The district of Vauban imposes an energy standard of 65 kWh per square meter per year on all buildings within the district (Scheurer and Newman 2009). This standard ensures a low cooling and heating demand as the buildings onsite are designed to harness the sun for passive heating needs. Intelligent heat recovery ventilation in many of the units works to recapture waste heat in air leaving the building. In extreme conditions, when heating becomes necessary, electrical units connected to onsite solar allow residents to heat their houses.

Black Water Treatment: Vauban was originally designed to use the standard city sewage treatment. A small number of projects have been able to transition their waste treatment to the local vacuum converter treatment plant.

Gray Water Treatment: Both standard city treatment of gray water and non-potable reuse are commonly found throughout Vauban.

Stormwater Management: Most of the stormwater runoff produced onsite is collected and repurposed as toilet and garden water. What is not treated this way is allowed to recharge the local watershed through the extensive green space included in the district design.

Centralized Amenities: Vauban is too large a community to completely share many of the traditional centralized amenities. Extensive community interaction and contribution is a high priority in Vauban however, and examples of community sharing occur through things such as car sharing or garden sharing. As the neighborhoods were independently designed, some spaces were built with a higher emphasis on unit interaction than others such as through shared fire pits and centralized plazas. No centralized amenities were designed for the entire district, however, due to its extensive size.

Combined Systems: Units taking advantage of vacuum conversion allow for the production of energy through the form of biogas while simultaneously treating their sewage and organic waste.

Rieselfeld

General: Rieselfeld is a commercial and residential community on the western side of Freiburg, Germany. The district master plan was designed through an urban development and landscape planning competition run by the city of Freiburg. The developed site is part of an old 320 acre sewage farm which served the south western part of Freiburg for more than 100 years. Remediation of the land allowed for the project construction and was funded by the city itself, with individual blocks sold entirely to one

investor or investor group (Baugruppen). Volunteer residents now work to protect the nature preserve onsite and educate residents about the necessary work onsite. The development was installed in four segments, spaced by two years each, to allow for “adaptive planning” as needed. Per the city plan, Rieselfeld is pedestrian oriented, with a backbone of walkable and bikeable green corridor running down the middle. The district is connected through public transportation to the main city. All units built onsite are required to meet a maximum level of energy consumption of 65 kWh per square meter per year (RPG 2009).

Figure 9: Site map of Rieselfeld (Monroe, 2012).

Size:	70 acres	Population:	~10,500	Density:	~150 people/acre
Electrical Supply:	Solar				
Cooling/Heating System:	Wood pellet heating; Heat pumps				
Black Water Treatment:	City				
Gray Water Treatment:	City				
Stormwater Management:	Collection; Green space for recharge				
Centralized Amenities:	Courtyards; Sports center; Meeting center; Schools; Church				
Combined Systems:	Cogeneration				

Table 8: Infrastructural breakdown of Rieselfeld.

Electrical Supply: Much of the district energy requirements are met through distributed solar sources. What is not met electrically this way is produced through the city power plant which harnesses cogeneration technologies.

Cooling/Heating System: Many of the structures onsite are capable of meeting their heating needs through passive heating due to the energy requirements. Some units have their own heat pumps and wood pellet heating which can produce any excess heat needed. Those which require an additional heating source are required to connect to the district power/heating plant which utilizes cogeneration techniques to provide heating.

Black Water Treatment: Standard per the city.

Gray Water Treatment: Standard per the city.

Stormwater Management: All of the stormwater runoff produced onsite is collected, filtered through a soil filter, and circulated into the wetland nature reserve.

Centralized Amenities: Rieselfeld is large enough to allow for an elementary school, a middle school and a high school. A district meeting center is also present for planning requirements and community events. A centralized “green wedge” serves as the district park, protecting the bordering nature reserve for relaxation seekers. A district policy of shared courtyards on every block encourages interaction between neighbors. A district sports center allows for local teams and sports clubs to form between community members.

Combined Systems: Cogeneration technologies employed within Rieselfeld capture waste heat from energy production and distribute this heat source throughout the community.

Hammarby Sjöstad

General: Hammarby Sjöstad is a district in Stockholm, Sweden. The project was built over an old brownfield site, which was once an industrial waterfront. Initially spurred by an Olympic bid which Sweden lost, the City of Stockholm shifted the site development towards that of a sustainable community. The site was remediated, and a master planned district was built in place. The area is developed to be extremely walkable, with a green pedestrian corridor running down the middle and easy access to grocery and retail shops sprinkled throughout. It also provides quick access to public transportation, and encourages the use of bike and car sharing services among residents. Each unit developed within the district is required to meet high energy standards, reducing the total reliance on energetic systems for heating and cooling. Strategically subsidized housing allows economic access to lower income residents within the community. Glashusett, the environmental center, provides proper education among residents on topics such as water saving devices helps to reduce water consumption by 50% within Hammarby Sjöstad helps to achieve the districts sustainability goals. (Urban Green-Blue Grids, 2018)

Wastewater is treated locally. The produced sludge is then used for farm and forestry land. Biogases released during the treatment process are collected and reused within the community for transportation, heating, and cooking needs. Heat is extracted from the treated water, allowing cold water to be distributed for cooling, and heated water to spread for heating purposes as needed. (Urban Green-Blue Grids, 2018)

Figure 10: First half of the Hammarby Sjöstad site map (Monroe, 2012).

HAMMARBY SJÖSTAD – ENVIRONMENTAL MAP

Figure 11: Second half of the Hammarby Sjöstad site map (Monroe, 2012).

Size:	420 acres	Population:	~24,000	Density:	57 people/acre
Electrical Supply:	Solar; Hydrogen fuel cell; Biogas				
Cooling/Heating System:	Passivehaus; Cogeneration; Heat exchange water loop				
Black Water Treatment:	Onsite treatment				
Gray Water Treatment:	Onsite treatment				
Stormwater Management:	Green roofs; Retention pond				
Centralized Amenities:	Cultural center; Chapel; Pre-school, primary and high schools; Library; Environmental center; Childcare; Healthcare				
Combined Systems:	Waste treatment/biogas production; Cogeneration				

Table 9: Infrastructural breakdown of Hammarby Sjöstad.

Electrical Supply: In Hammarby Sjöstad, many efforts are made to provide opportunity for alternative energy options, such as through the installation of biogas cooking stoves. This gas is produced onsite through the waste treatment system. Solar cells are able to provide an additional source of electricity supply. A hydrogen gas fuel cell works to produce both heat and electricity through hydrogen combustion.

Cooling/Heating System: Many of the units within Hammarby Sjöstad are designed to passively meet their heating needs. What else is required throughout the district is distributed through a district wide water loop system. As of 2002, roughly 34% of the heating needs came from purified wastewater, 47% from combustible household waste, and 16% from biofuel (Urban Green-Blue Grids, 2018). The district is cooled through cold water generated when heat is extracted from purified waste water. This serves cooling needs such as cold storage within grocery stores.

Black Water Treatment: A district waste treatment plant treats all of the black water onsite.

Gray Water Treatment: Gray water is treated onsite through the waste water treatment plant.

Stormwater Management: Green roofs throughout the district work to buffer the district's stormwater treatment needs. What stormwater is not absorbed through the green roofs is captured, drained to treatment/retention ponds, and allowed to recharge the groundwater system.

Centralized Amenities: The size of Hammarby Sjöstad means that the type of centralized amenities are on a macro scale. These include twelve preschools, three primary schools, two high schools, a library, healthcare and childcare facilities. A cultural and environmental center are present to further education about the sustainability goals of the community, and foster a sense of community. A chapel is also provided for religious needs in the community. Individual units maintain all of the amenities of typical market rate housing however, keeping such things as cooking and laundry decentralized.

Combined Systems: The district waste treatment plant is intricately linked with the district heating and energy supply systems. Biogas produced through the waste treatment process is collected and used to power vehicles and provide fuel for cooking in some of the units. Waste heat extracted from the waste water provides a heating source, while the leftover chilled water provides a source of cooling where needed.

Västra Hamnen

General: Västra Hamnen is a redeveloped industrial shipping yard in Malmö, Sweden. The district houses 10,000 residents and Malmö University, which serves 20,000 employees and students. The district was developed for the 2001 European Housing Expo as the “City of Tomorrow”. It is an investment made by the City of Malmö to increase its attractiveness as a place in which to live and work. As a remediation and redevelopment strategy for an old shipping yard and dump, one of the main design goals was to increase the biodiversity in the area. This involved strategic habitat restoration for local flora and fauna. 100% clean energy and transportation alternatives were another goal of the development. These goals are met through a walkable/bikeable design and solar/wind electrical supplies. High energy efficiency is required of all units constructed onsite, which works to ease the electrical demand. The site takes advantage of its location through the use of the underlying aquifer which it effectively uses to exchange heat with throughout the year. (City of Malmo, 2006)

Figure 12: Site map of Västra Hamnen (Monroe, 2012).

Size:	395 acres	Population:	~20,000	Density:	~50 people/acre
Electrical Supply:	Solar; Wind; City as needed				
Cooling/Heating System:	Geothermal water loop				
Black Water Treatment:	City				
Gray Water Treatment:	City				
Stormwater Management:	Green roofs; Retention ponds				
Centralized Amenities:	Park and Plazas; University				
Combined Systems:	None				

Table 10: Infrastructural breakdown of Västra Hamnen.

Electrical Supply: All of the electrical needs in the district of Västra Hamnen are met through solar and wind power. During annual cycles where the district does not produce as much energy as they need, they borrow from the city's power grid and give back during months of excess power production.

Cooling/Heating System: The district uses a heat pump to store and remove heat from the warm waters of the adjacent bay and underlying aquifer. These waters are then circulated throughout the district to meet the needs of individual units.

Black Water Treatment: Standard per the city.

Gray Water Treatment: Standard per the city.

Stormwater Management: Green roofs distributed throughout the district buffer the amount of stormwater necessary to treat. Excess runoff is then captured and filtered in retention ponds and then allowed to return to the adjacent ocean.

Centralized Amenities: Standard amenities are provided with each unit in the district. Centralized amenities for the district include provided schooling as well as centralized areas for social meeting to occur, such as parks and regularly spaced plazas.

Combined Systems: None

Implementation Strategies

One of the major challenges facing district design is the amount of required land. There are a multitude of ways to address this challenge and bring that land into development under one single owner. Examples that arose during research for this thesis are as follows:

Campus

One of the most common methods leading to district design is the development of a campus. These projects generally require massive amounts of funding. Because of this, they are often done either for a university, or for a large business, who have a strong interest for a large connected work district. Campus projects are inherently district scale projects, and thus can easily leverage the benefits of centralized infrastructure systems into their design. The desires of the ultimate owner often drive these projects. Design work is usually done in a collaborative method with an exterior consulting firm contracted out. An example of such a project is Malmö University of the Västra Hamnen project.

Repurposing

A second very common method in district design is the repurposing of abandoned, large scale projects. Examples of such projects include abandoned shipping yards or military bases. These projects are often developed by master planners or are self-driven by the owner to increase the value of their property. These projects offer opportunity to breathe new life into what would be discarded as rubble. This reuse of location and material is environmentally sustainable. Often such projects are built over historically polluted locations, such as brownfields, leading to remediation of the site. As these projects increase the public desire to visit such locations, they also increase the social sustainability of the site. These sites are often either bought at a discounted price, and dramatically improve the value of the property, making them an economic investment. Unfortunately, as many such projects require renovations or remediation, the additional investment required beyond the initial price can dampen the economic benefits. An example of such a project is Vauban, which is a repurposed military base.

Master Planner

It is common for district scale projects to be driven by a “master planner” or one single organization who works to develop property and sells the developed units for a profit. Single owner development requires that single owner to be wealthy enough to fund the entire project themselves. In such cases, profit is often the main driver. The development is designed by the master planner and sold to the ultimate owner for profit. As profit is the main driver, this can have a negative impact on the sustainability goals of the project unless carefully considered throughout the entire planning phase. An example of such a project is the Goings Street Commons designed and built by Birdsmouth Construction.

Community Real-estate

One funding technique growing in popularity is “group buying”. This involves the organization of like-minded individuals pooling their resources to buy property. The design/development work is either hired out or taken upon by the individuals involved. It is primarily the desires of the organization that drive these projects rather than profit. These projects often have smaller budgets however, due to the amount of money afforded by individuals versus large companies. Due to this, it is not uncommon that a group of individuals will purchase one large house in which to live together on the property. Such projects can manifest in multiple ways. One common example is when a group of unrelated individuals buy a house and live in the existing rooms, adding on as needed and sharing the existing community space. A second example is when individuals live in small dwelling units on the property and share the main house as community space. Through group investment in multiple adjacent properties, such organizations can slowly grow in a typical urban setting without the same investment as is often required for district design projects. This cohousing strategy is extremely accessible financially to lower income individuals, and thus economically sustainable.

A second manifestation of community real-estate that can arise is when a wealthier group of individuals is able to buy a large piece of property to develop. A larger budget allows for more intricate development. Unfortunately, due to the nature of such projects being financially inaccessible to many lower income individuals, these projects often have a tendency to become rather elite and exclusive. This can be avoided however if intention for socio-economic accessibility is kept in mind during the planning phases. An example of such a project is Vauban. Only a section of this community was developed under the community real estate method (also called Baugruppe).

Utility Driven

Utility driven district development refers purely to the development of centralized infrastructure, and generally not to the dwelling units or commercial spaces often associated with district design. Often these projects are limited to one infrastructure type, such as a multi-neighborhood electrical system. To some extent, this is how many utilities are currently developed, such as waste treatment, only on a much larger, city-wide scale. Projects aiming to change the traditional utility scale are rare, and often extremely challenging to navigate policy wise. An example of such a project is the Brewery Blocks which are linked together through a multi-building heating and cooling system.

Social Benefits

One of the benefits of district design is its ability to encourage residents to interact with one another through form. This is important, as it has been proven that “(a)ctual and perceived isolation are both associated with increased risk for early mortality” (Holt-Lunstad et al., 2015). In a meta-analytical review of loneliness and social isolation risk factors for mortality, social isolation, loneliness and living alone “corresponded to an average of 29%, 26% and 32% increased likelihood of mortality, respectively” (Holt-Lunstad et al., 2015). Community housing, such as found in many district designs, can help combat this by working to build strategic moments where people interact with one another on a regular basis (McCamant et al., 2011). Examples of such strategic moments can include community gathering centers, community gardens, centralized mailboxes, or edible plants placed between the doorways of neighbors. District design lends itself beautifully to the creation of such spaces. This can easily increase the quality of life of the residents within, and thus the social sustainability of the entire project.

Pandora Patterson, a resident of Kailash Ecovillage, expressed the sentiment that both she and many others within her district felt that they were happier living in a communal area. They felt more supported and connected to those around them. This sentiment, echoed throughout accounts from other district residents, is important for all levels of life. This especially applies for very young and elderly populations when complete self-sufficiency is not a realistic option.

Over the past 50 years, household sizes have been decreasing, while the average footprint of a house has been increasing (Peterson, 2018). This has brought about a dramatic increase in residential footprint per capita, a trend that is still increasing (see Figure 13). This means an increase in isolation, which as stated earlier, has a negative impact on both quality of life and life expectancy (Holt-Lundstad et al., 2015). These issues can easily be addressed through district design.

Figure 13: A Graphical exhibit of the growing trend in residential footprint per capita. (Peterson, 2018)

Specific Considerations for Social Sustainability

Specific and necessary design strategies and parameters for sustainable district design arose during research for this thesis. Though they do not encompass all the necessary considerations, they are critical to the success of the projects studied in this thesis. They are as follows:

Density

Density is a limiting parameter in sustainable district design for multiple reasons. Economically, higher occupant density allows for lower prices per unit on average, and/or a decrease in the project payback period. This means that lower income individuals can reside within the project, and/or the project becomes more attractive to invest in. These work together to help increase both the social and economic sustainability of the project. Density is also a key component when scaling and applying infrastructure systems. The required energetic inputs and outputs determine the feasibility of any infrastructure system to function.

Distribution of Power

The power structure within any community has a significant impact on its social equity. When multiple individuals or businesses share the same amenities and location, how decisions are made regarding those resources becomes a complex topic. Some districts elect a council to make decisions for the entire community, such as in the Going Street Commons. Some districts have a purely democratic system, where every resident has an equal vote. Some districts, such as the Kailash Ecovillage, are run as businesses, and the business owners are allowed the final decision on all subjects. Whether a district is developed to be sold as a package (as through master planning) or by the residents who will reside within (as through community real-estate) it is important that community power distribution be considered during the design phase of any district project

Education

As district design is not a common or traditional method of creating a space, it is important to educate residents and visitors about the specifics involved. This serves multiple purposes. First, residents need to understand the general rules of their community (e.g. how tools and food are shared, how the composting system functions, community space rules, who to contact if something is broken) for the social and physical systems to function properly. Second, in order to further the understanding of district design and its potential benefits, education is needed to spread knowledge of an uncommon subject. Examples include the efficiency benefits of a district wide chiller loop, or how infrastructure systems within the district have been sized to interact with one another, such as waste treatment creating biogas.

Personal Space

Though isolation is directly linked to increased risk for early mortality (Holt-Lunstad et al., 2015), this should not negate the human need for personal space. When designing community housing, as district design often does, it is important to include opportunities for quiet, personal space, for all residents involved. Without this, residents may become socially overwhelmed and come resent the community that they live in. This can easily be addressed through assured individual bedrooms for all residents where they can escape to if needed.

Access to Green Space

“There is growing evidence that contact with nature and physical activity in nature has considerable positive effects on human health” (Brymer et al., 2012). This means that in order to maximize the social sustainability of a district project, access to nature and green spaces must be considered, either through location choice or design. This can be through proximity to a park, or simply through provided lawn, garden, or natural courtyard area. These areas will not only have positive effects on the health of residents, but also provide habitat for local species, increasing environmental sustainability. Gardens can be used to provide food to residents, increasing economic sustainability, while encouraging residential interaction, increasing social sustainability. Natural areas often have pervious soils and can be harnessed for onsite stormwater treatment, a necessary infrastructure system that is often neglected. Natural areas, such as parks, have also been linked to a decrease in the heat island effect (Feyisa et al., 2013), increasing the environmental sustainability of a district even further.

Moments of Interaction

As stated earlier, social interaction bolsters community and has positive effects on quality of life and life expectancy. District design provides many opportunities for moments of interaction. These can be leveraged for maximum efficiency if they are carefully considered during the design period. One strategy involves adding a centralized location for residents to carry out daily individual tasks in a communal setting, such as the gathering of mail. Another strategy involves adding objects in areas of possible interaction that would slow individuals down, allowing them to pause and interact. An example of this is edible plants between the houses of adjacent neighbors. A third strategy is simply to allow space for communal gatherings, such as an event hall or communal courtyard. A fourth strategy is to create opportunities for sharing and interaction, as with a communal tool shed or garden.

Technical Data

As shown earlier, there are many ways to share infrastructure systems. The following section of this thesis aims to compare strategies for sharing infrastructure systems at non-traditional scales, and compare them, with regards to the triple bottom line, to traditional systems.

Centralized Amenities

Amenities are spaces which help to provide comfort, convenience, and enjoyment. These spaces are often considered optional additions when designing a district but have the potential to greatly improve the quality of life experienced by residents. In general, each type of amenity has a specific scale at which it is socially considered a necessity but can easily be scaled to serve a wide range of district sizes depending on the demands.

Communal Space

Communal spaces serve as gathering spaces for residents, workers, or for the public. The target audience of such spaces depends on the context through which they are presented. Communal spaces are often considered mandatory both on a macro and micro level for the social well-being of a society. A common micro level example is the living room, which is found in most modern homes. Porches, lounge rooms and courtyards are also examples of micro scale communal spaces. These micro-scale communal spaces serve to allow private social events often reserved for one family and their close friends.

On a macro level, communal spaces include such things as parks and event centers. These spaces serve for larger gatherings, including cultural and religious celebrations, performances, and public meetings. These spaces are epicenters for communal growth and the strengthening of communal bonds. In district design, these spaces are extremely important when designing to encourage community interaction. Communal spaces are often cheap to build, as they simply require the allocation of space. Many communal spaces are designed to be indoors to allow for year-round events, and thus may be more expensive. Once built however, these spaces provide free access to all socio-economic groups. They cater to a wide diversity of individuals as they offer space for all religious and cultural celebrations. Communal spaces are a cheap way to vastly improve the social sustainability of any community design.

Appliance-Dominated Amenities

Appliance-dominated amenities refer to spaces which are utility driven and revolve heavily around appliance usage. In modern American homes, these spaces are socially dictated to be included separately in each unit. Certain social conditions allow for this to easily change, however. For example,

laundry rooms are commonly shared in many apartment buildings, rather than every unit housing its own washer and dryer. Dorms are often designed to share one shower room per floor, instead of each unit containing its own bath and shower. Kitchens are a third example of an appliance-dominated amenity which are rarely shared except in housing co-ops.

Centralizing these amenities to be shared and used by more than one unit allows for a massive reduction in the amount of piping and appliances required for installation. This significantly lowers the embodied carbon of a development, as well as the cost of the initial investment, making it highly economically and environmentally sustainable. By centralizing such regularly used amenities, residents are also encouraged to interact with one another on a regular basis, allowing for growth in stronger community bonds and increased social sustainability. This especially applies toward kitchen spaces, which centralize around food, a common communal activity in many cultures. Unfortunately, social stigmas currently view this practice as only acceptable in certain circumstances and not in others. For example, communal showering is considered acceptable in a dormitory setting but not in hotels or private apartments. This social bias has the potential to deter residents from participating in the sharing of appliance-dominated amenities, and thus greatly reducing the social sustainability of the district design.

It should be noted that the scale at which centralized appliance-dominated amenities are applied is severely limited by walking distance. Residents and workers are often not interested in walking more than a few minutes to reach such amenities, and thus they can only be designed to serve communities with relatively small footprints.

Gardens

Gardens range in size from a few personal pots to acres of farm land. They are spaces in which individuals grow and care for plants, often edible or ornamental. Studies have shown that along with food production, gardening can act as therapeutic treatment for a wide range of patients, from the elderly and demented (Gonzalez and Kirkevold, 2013) to patients in rehabilitation centers (Söderback et al., 2009). Communal gardens further improve the quality of participant's life by encouraging social bonding through joint investment and celebration of a project raised. Whether organized as a series of individual plots, one communally cared for space, or a combination of the two, gardens are extremely socially sustainable. The benefits of local food production contribute both to the environmental and economic sustainability of any district design in which a garden is introduced.

Gardens are also an excellent retrofit solution to encourage neighborhood community interaction. Abandoned lots can easily be transformed into a garden space if the soil is toxin free. Locally produced fertilizers through waste treatment can easily be applied to such areas to further the economic and environmental sustainability of the project.

Share Sheds

Share sheds are simply spaces in which goods are placed to be used by multiple users within the district community. Such items can include food, household goods, tools, or even cars and bicycles. This technique allows for waste reduction, as products no longer desired by one community member can be used by another in need instead of proceeding to the landfill. Community consumption also decreases, as supplies can be used by more than one owner rather than bought by each individual. Many campuses employ the use of share sheds and share rooms to ease the financial burden on their student residents.

Communally led examples of share sheds can occasionally be found built into the sidewalk medians of city neighborhoods.

Though not the most common technique, share sheds are extremely sustainable, economically, environmentally and socially. Economically, because they allow free access to needed goods easing the financial burden on participants. Environmentally, because they reduce the consumption and waste production of participating communities. Socially, because they encourage sharing and caring within participating communities. A share shed retrofit, with either an open or targeted purpose, is a simple and cheap way to increase the sustainability of any district design.

Transportation

Centralized transportation can present itself in multiple forms. The most common is on a macro level, through public transportation provided by cities. On a smaller scale, some districts practice the organized use of cars, bikes, and/or ride sharing among the residents and workers. In either case, the sharing of transportation options can greatly reduce the number of autonomous vehicles in a district. This reduces the amount of traffic present within the district, thus reducing commute times and the emissions produced by autonomous vehicles. As stated in the “Share Sheds” section, the sharing of vehicles, as with any commodity, causes a reduction in consumption, waste production, and an increase in community interaction.

Centralized transportation systems, on any scale, increase the sustainability of any district in all sustainability categories. Environmentally, through reduced consumption and waste/emissions production. Economically, through the increase in access to transportation options and decrease in maintenance costs due to wear-and-tear on the roads. Socially, through the encouragement of community interaction and sharing among residents, and the increase in life quality for commuters no longer stuck in traffic.

Schools, Healthcare, Childcare

Schools, healthcare, and childcare are all examples of social services every community needs. Though costly, many people require these services to live a full, healthy, productive life, and are thus worth the economic investment. Without such services, a community will be unable to educate itself, or take care of its health, youth, and working parents. This means that to be economically and socially sustainable, access to these services is required within a community. The size of the community served however has a massive impact on the viability of these services. If a community is too small, the economic investment required is often completely unfeasible. Construction of such services becomes necessary when considering district designs on a macro scale.

It should be noted that when designing a district, needs of the surrounding community should be considered rather than just those of the residents and workers. If access to schools, childcare, or healthcare are lacking in the surrounding community, providing them within the district itself is just as necessary for district residents as well as residents in the surrounding community.

Stormwater Management

As cities continue to densify, building roads, parking lots and buildings, the ratio of impermeable to permeable surfaces in urban landscapes is increasing. This leads to an increase in the amount of runoff produced during storm events. This water carries with it dirt, oil, and other pollutants. Traditionally, this runoff is directed off the street into an underground piping network where it is carried to a city's

centralized wastewater treatment plant or directly into the local river. This excess amount of water arrives in a nearly instantaneous spike, easily causing combined sewer overflow (CSO) events and disrupting the natural hydrologic cycle. This has many negative impacts including public health concerns, increasing flooding events, and damaging the local ecosystem. By allowing stormwater runoff the ability to trickle through the earth and return to the local watershed, the peak amount of water arriving to local treatment plants and rivers can be lessened, decreasing the occurrences and effects of these negative impacts (City of Portland, 2016). Strategies to address stormwater are outlined below.

Combined Sewer Systems

Combined stormwater and sewer systems funnel stormwater runoff directly into the sewer system. Historically, this has been one of the most common way to address runoff. This system allows the district in question to treat stormwater runoff at the wastewater treatment plant before allowing it to return to the watershed. These systems are often overwhelmed during major storm events, resulting in CSO events, creating environmental hazards and public health concerns. This reduces both the environmental and social sustainability of this strategy. These negative consequences are in fact so bad that according to the EPA, “state and local authorities generally have not allowed the construction of new combined sewers since the first half of the 20th century” (EPA, 2018)

Installation of combined sewer systems requires the construction of large amounts of piping beneath the district, which can be expensive especially when sized to specifically avoid CSOs. An excellent example of such a project is Portland Oregon’s “Big Pipe” project, which cost \$1.4 billion and allowed for a 94% reduction in CSO events (City of Portland, n.d.). The population of Portland continues to grow however, along with development in the area, causing an increase in demand upon the Big Pipe. At such a high price, it is not economically sustainable to build a larger pipe once this one becomes overtaxed by increasing runoff and sewage. Because of this, Portland is changing its stormwater strategy to onsite treatment methods, examples of which are described below (City of Portland, 2016).

Collection/Reuse

Stormwater can be collected using rain barrels and/or cisterns. These systems funnel rain water through a gutter system off of buildings and into storage tanks. This water can be treated, often through a UV system, or using chlorinated tablets, and reused for potable needs. Very little conclusive research has been done on the effectiveness of the cheaper filtration strategies however, and therefore this is often either prohibitively costly or potentially unsafe. Instead it is more common that this collected water be used for non-potable necessities such as garden/yard irrigation or to flush toilets. This strategy either allows the stormwater to return to the local watershed through infiltration, reducing its contribution to peak stormwater impacts, or allows it to mingle with black water while lessening a district’s demand for fresh water through non-potable reuse.

Reuse through irrigation is a cheap, simple retrofit that is both environmentally and economically sustainable. Reuse through flushing can require large amounts of infrastructure and therefore can be a costly retrofit. The uncertainty in the amount provided as a source also demands that these systems remain supplied by other sources such as city water. This means that often, if applied as a retrofit, such reuse is not economically sustainable. When analyzed for embodied carbon, such a retrofit is often not very environmentally sustainable either. Collection systems often require maintenance and attention throughout the year as they are extremely susceptible to freeze/thaw events and can act as hosts to mosquitos. Because of the high level of required maintenance, they are not particularly socially

sustainable, as such systems can appear more of a burden than a blessing to individuals accustomed to little to no maintenance of their stormwater systems.

Green Roofs

Green roofs or garden roofs alleviate stormwater runoff by using plants to absorb rain fall onto building roofs before it becomes runoff. These systems also help to reduce the amount of heat reflected by a building's roof, reducing its impact on the heat island effect. These gardens can be used for local food production if desired, increasing social interaction and the environmental and social sustainability of this strategy. It should be noted that many green roofs are designed to be as drought tolerant as possible to reduce the level of maintenance required, so are not always the best garden locations.

Gravity loads generated by green roofs are much higher than that of a typical roof, as they are much heavier. This means that buildings must be designed or retrofit to handle this additional load upon green roof installation, which can be cost prohibitive. These systems are not equipped to store large amounts of water, and therefore should not be used as the only strategy in a stormwater plan. They are however excellent at reducing the initial amount of runoff produced, and thus the burden on all other systems used.

Rain gardens/Bioswales

Rain gardens and bioswales are low-level planters into which stormwater actively drains. The plants work to remove pollutants from the runoff through phytoremediative uptake. Rain gardens are much shallower than bioswales, and therefore have a smaller treatment capacity. Plants chosen for rain gardens are often chosen for food production, as ornamentals, or for pollinator habitat. Plants chosen for bioswales are specifically drought/flood tolerant in order to handle the wide range of watering experienced throughout the year and minimize required maintenance. These systems require regular clearing of stormwater entry drains, and occasional weeding, though the maintenance is relatively minimal. They are relatively cheap to install, making them economically sustainable, and generally attractive, making them socially sustainable. By providing ecosystem habitat for pollinators and allowing the local watershed to replenish, they are also environmentally sustainable.

Retention Ponds

Retention ponds are man-made ponds which can store copious amounts of stormwater, allowing it to return to the local watershed through infiltration. These ponds are often very cheap to build, making them economically sustainable. They are restricted however by the amount of land available and are therefore often not a feasible treatment strategy in dense urban environments. Some ponds are designed to function as attractive park features, with fountains and a surrounding playground. This strategy, though more expensive, allows for the addition of a park in the district, increasing green space and social sustainability. Encouragement of water flow within the pond also deters mosquito growth, which can be an issue in more stagnant retention ponds. These ponds can function to provide habitat for local fauna, such as birds, which increases the environmental sustainability of this strategy.

Electricity

According to the US Energy Information Administration, the US currently produces 32% of its electricity through natural gas, 30% through coal combustion, 20% through nuclear production and 7% through hydroelectric (U.S. Department of Energy, n.d.). These plants are generally rather large, with one or two plants serving an entire county. These large electrical systems are both less resilient and less efficient

than onsite electricity production. This is because, as with all large centralized infrastructure, if the centralized plant is damaged, the area and number of people effected and left without electricity is much greater than for smaller generation plants. Localized power sources also require less infrastructure, such as power lines, to transport the energy created. As power transportation is not 100% efficient, transportation makes the entire energy production method less efficient. When choosing an electrical production method, the surrounding environment and climate must be considered as many electricity generation methods are highly subject to environmental factors. Not all generation choices are suitable for every climate.

Solar

Many of the districts studied in this thesis rely heavily on solar power. This is because solar is a cheap, renewable energy source which requires minimal maintenance upon installation. Solar energy is also accessible to almost all districts, as the sun shines almost everywhere on earth. Some districts are limited by size. If a district is built vertically, with a very high density, solar panels may not be efficient enough to serve the entire community. They require a large area with direct access to the open sky and sunshine. Solar power is often seasonally influenced, depending on a site's latitude. This requires excess energy produced during sunny seasons to be stored for dark seasons, or a secondary energy source. As a cheap, renewable, emission free electrical production strategy, solar panels are sustainable environmentally, economically and socially.

Combustion

One can combust many different substances to produce electricity. Each substance comes with its own concerns with regards to efficiency and the emissions produced. Substances producing low levels of greenhouse gases during combustion (e.g. natural gas) are referred to as “clean burning” fuels. These are more environmentally sustainable than those producing high levels of greenhouse gases (e.g. coal). See Tables 11 and 12 for emission and efficiency comparison examples.

Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (subbituminous)	214.3
Diesel fuel and heating oil	161.3
Gasoline (without ethanol)	157.2
Propane	139.0
Natural gas	117.0

Table 11: Pounds of CO2 emitted per million British thermal units (Btu) of energy for various fuels. (EIA, 2017)

Table 7.3. Average Quality of Fossil Fuel Receipts for the Electric Power Industry,
2006 through 2016

Period	Coal			Petroleum			Natural Gas
	Average Btu per Pound	Average Sulfur Percent by Weight	Average Ash Percent by Weight	Average Btu per Gallon	Average Sulfur Percent by Weight	Average Ash Percent by Weight	Average Btu per Cubic Foot
2006	10,063	0.97	9.0	143,883	2.31	0.2	1,027
2007	10,028	0.96	8.8	144,546	2.10	0.1	1,027
2008	9,947	0.97	9.0	142,205	2.21	0.3	1,027
2009	9,902	1.01	8.9	141,321	2.14	0.2	1,025
2010	9,842	1.16	8.8	140,598	2.14	0.2	1,022
2011	9,762	1.19	8.8	139,795	2.49	0.4	1,021
2012	9,668	1.25	8.8	139,567	3.61	0.5	1,023
2013	9,661	1.29	8.7	139,671	3.54	0.5	1,026
2014	9,710	1.32	8.6	139,713	3.56	0.5	1,029
2015	9,634	1.29	8.6	139,681	3.38	0.5	1,034
2016	9,617	1.34	8.7	138,384	3.69	0.5	1,034

* = Value is less than half of the smallest unit of measure. (e.g., for values with no decimals, the smallest unit is 1 then values under 0.5 are shown as *.)

NM = Not meaningful due to large relative standard error or excessive percentage change.

W = Withheld to avoid disclosure of individual company data.

Notes:

Beginning in January 2013, the threshold for reporting fuel receipts data was changed from 50 megawatts to 200 megawatts of nameplate capacity for plants primarily fueled by natural gas, petroleum coke, distillate fuel oil, and residual fuel oil. In addition, the requirement to report self-produced and minor fuels, i.e., blast furnace gas, other manufactured gases, kerosene, jet fuel, propane, and waste oils was eliminated. The threshold for coal plants remained at 50 megawatts. The following caveats for each fuel type should be noted:

COAL - includes anthracite, bituminous, subbituminous, lignite, waste coal, and coal-derived synthesis gas. Prior to 2011, synthesis gas was included in the category of Other Gases.

PETROLEUM - Includes petroleum liquids (distillate fuel oil and residual fuel oil) and petroleum coke which includes petroleum coke-derived synthesis gas. Prior to 2011, petroleum coke-derived synthesis gas was included in Other Gases. Prior to 2013, petroleum liquids included distillate fuel oil, residual fuel oil, kerosene, jet fuel, waste oil, and, beginning in 2011, propane. Prior to 2011, propane was included in the category of Other Gases.

NATURAL GAS - Includes natural gas only. Prior to 2011, includes Other Gases.

Table 12: Efficiency comparison of fossil fuel combustion. It should be noted that this table is not normalized by volume measurement and is thus not necessarily the best comparison example. (EIA, 2016)

The source and cost of combustible fuel used also contributes to the sustainability of electrical production through combustion. For example, biogas is an extremely affordable fuel produced as a bi-product of black water treatment. This fuel source has a high economic sustainability, as it is already produced naturally through necessary tasks to support a community, and thus only requires the initial investment in capturing infrastructure. Biogas is also a clean burning, renewable fuel with a minimally invasive production process, making it highly environmentally sustainable. Coal is an example of a cheap and accessible fuel, thus economically sustainable, but which has social and environmental sustainability concerns. The emissions produced by burning coal carry high concentrations of greenhouse gases and particulate matter. The mining process is highly invasive and can have detrimental impacts on the health of the workers. These concerns lead coal to be an unsustainable fuel source, both socially and environmentally.

Combustion systems can be scaled to service a wide range of areas. From individual dwelling units (e.g. gas generators) to entire counties (e.g. coal combustion plants), combustion systems are not limited by density. The sustainability of these systems depends entirely on the fuel source.

Nuclear

Nuclear energy is a highly controversial energy source. Currently, no known treatment exists for the radioactive waste created in the production process. According to the World Nuclear Association, “deep geological disposal is widely agreed to be the best solution for final disposal of the most radioactive waste produced.” Some of the most common high-level waste materials created during nuclear energy production are uranium (U-238, U-235 and U-234) and plutonium-239. These materials have half-lives of about 2.5 billion years, 700 million years, 25,000 years and 24,000 years respectively (DUF6 Storage, n.d.) (Forsberg, 1997), meaning that they decay extremely slowly. Often these waste materials can be reused for further power production. When they are ready for disposal however, the only current solution is storage and/or burial. Proper site location for the deep burial of nuclear waste can protect it

from leaking into local groundwater sheds, but can be extremely difficult to locate, as there are many requirements including no potential for local seismic activity or watershed interaction. Many individuals believe that this strategy poses potential human and environmental health risks due to leaks in plant and above ground storage. This makes nuclear energy unsustainable environmentally and socially.

The benefits of nuclear energy are embodied through its cheap cost, small production plant footprint, and ability to be unconstrained by the surrounding environment. Nuclear energy is a relatively cheap energy source due to high production efficiency, making it economically sustainable. This may change if regulations on the waste produced become more stringent, but currently nuclear energy is a viable option for communities requiring substantial amounts of cheap power. The amount of area required to produce nuclear power is much smaller than that required for combustion plants or hydroelectric dams. This makes it a more feasible option for communities limited by the amount of land available. Unlike many energy sources, the only requirement for nuclear energy production is a production facility, and the ability to dispose of the produced waste. This makes nuclear energy a viable option for communities where the conditions necessary for wind, solar, geothermal, and hydroelectric energy sources are not present. In summation, the current low cost of continuous nuclear energy production makes it relatively economically sustainable, but health concerns associated with nuclear energy production make it unsustainable both environmentally and socially.

Hydroelectric

Hydroelectric power production is the harnessing of electricity through conversion of the kinetic energy of a running river through a turbine. This form of energy production requires large amounts of infrastructure installation and a large body of running water. Because of this, this strategy is not economically suitable for small-scale districts, nor for districts without a large source of annually running water. Once the initial installation cost is complete, hydroelectric power is a relatively cheap energy source, as the input energy is continuous and already in place preconstruction. This makes hydroelectric power an economically sustainable power source for large communities in suitable locations. Constant maintenance of the dam is required, but this is not too difficult if the original facility has been designed properly.

Environmentally, hydroelectric power produces no emissions, and is therefore considered to be a clean, renewable power source. Large hydroelectric plants have a major impact on the downstream ecosystem of the watershed and can be harmful to migratory fish populations. These effects can be limited with the proper design of fish passages and downstream flow releases. As a whole, hydroelectric power is a relatively environmentally sustainable power source, as it is clean and renewable, but the plant must be properly designed and run to care for the surrounding fauna.

Hydroelectric plants use large dams, which often create large lakes and reservoirs in the river basin for recreational activities. These spaces are often enjoyed by the surrounding communities for outdoor water recreation, raising the social sustainability of this strategy. The large dams associated with hydroelectric power can be used to control water flow, allowing for significant control over flood events, also raising its social sustainability. The potential negative impact on migratory fish populations can have a negative impact on communities relying on fish as a food and income source however, which can lower the social and economic sustainability of hydroelectric power. As a whole, many people consider hydroelectric power socially sustainable, as long as it is designed and run to care for and consider all impacted communities up and downstream.

Wind

Electrical production through wind involves the use of large turbines designed to capture the kinetic energy of the wind, similar to hydroelectric power and water. This is an emissions free, clean, renewable energy source. These large turbines require regular wind currents to operate effectively. As wind is not constantly blowing with sufficient speeds in most areas, wind turbines are not generally as effective as hydroelectric turbines. Because of this, a large amount of land is required to produce enough energy for an entire community. These turbines are also often expensive, and thus many communities are unable to invest in the initial infrastructure needed to power their district purely with wind power. Once the initial investment has been made however, the production of wind energy is free beyond the maintenance required. The pay-back period of such an investment can make wind energy economically unsustainable for many communities however.

Wind turbines have been known to shred bird flocks unlucky enough to ride the wind currents through. This fact lowers the environmental sustainability of electrical production using wind. The fact that wind is a clean renewable resource however, significantly raises its environmental sustainability. As a clean energy source, wind power has little to no impact on the public health of the surrounding community, making it a socially sustainable energy source.

Fuel Cells

Fuel cells produce electricity through a chemical reaction without combustion. Many types of fuel cells exist, for many fuel types such as ethanol, methanol, biogas and hydrogen. Hydrogen fuel cells, one of the most popular fuel cell types, convert hydrogen and oxygen into water producing electricity and heat in the process. "Fuel cells are 2 to 3 times more efficient than combustion engines. For co-generation applications, where fuel cells generate both heat and electricity, efficiencies can be close to 80%" (CHFCA, n.d.). Fuel cells can be scaled to power anything from a single car, to a multi-neighborhood district. As a clean energy source, fuel cells are an environmentally and socially sustainable electrical production strategy. They have flexible use, require minimal investment into the initial infrastructure, and use cheap fuel sources, some of which can be produced onsite, such as biogas. This makes fuel cells economically sustainable for many communities, especially communities on a micro scale.

Geothermal

Geothermal energy production uses the heat of the earth to power steam driven turbines. This power source is extremely limited by location and is consequently not available to all districts. It is a renewable, emission free energy source when available, however, making it highly environmentally and socially sustainable. The infrastructure necessary is not extensive but is larger than many small districts can afford. The lack of emissions produced make geothermal energy a socially sustainable energy source. If location permits, and the initial investment is present, geothermal energy is environmentally, socially and often economically sustainable as an electricity source.

Black Water Treatment

Decentralized black water treatment is extremely rare due to the associated sanitary public health concerns. According to the EPA, black water treatment "is among the most important factors responsible for the general level of good health enjoyed in the United States" (EPA, 2018). Because of this, sewage treatment is often sized to service whole counties ensuring strict treatment standards. This is historically done through combined or separate sanitary sewer systems. Because of the elevated

levels of public health concerns, social stigmas, and the large economic investment into these systems, a vast majority of districts choose to remain connected to the standard, city wide sewage system.

Combined Sewer Systems

Combined sewer systems integrate stormwater drainage. The pollutants carried by stormwater are often very different from those found in sewage, and therefore require different methods of treatment. Additional concerns are described within the “Stormwater Management” section. These systems have such negative public health and environmental impacts that they are illegal to build in many parts of the US.

Separate Sanitary Sewer Systems

Separate sanitary sewer systems are designed to collect wastewater only and are therefore not susceptible to the COCs caused by large storm events. This makes them much more environmentally sustainable than combined sewer systems. Leaky systems can cause sanitary system overflows (SSOs) however, which carry with them high levels of public and environmental health concerns. As with all black water treatment systems it is extremely important to regularly monitoring and maintenance the system.

Separate sanitary sewer systems require substantial amounts of infrastructure and are therefore often cost prohibitive to develop on a small district scale. Sewage in both combined and separate sanitary sewer systems is often treated biologically using microorganisms to break down human waste. This generates heat, and substantial amounts of methane, both of which can be harnessed as described in the “Combined Systems” section of this paper.

Septic Tanks

According to the National Environmental Services Center (NESC) of West Virginia University (WVU), “A septic system is a highly efficient, self-contained, underground wastewater treatment system. Because septic systems treat and dispose of household wastewater onsite, they are often more economical than centralized sewer systems in rural areas where lot sizes are larger and houses are spaced widely apart.” The system consists of two parts: a septic tank and a drain field. The septic tank retains waste, allowing liquids and solids to separate. Solid sludge sinks to the bottom, light pollutants such as oils float to the top, and a layer of partially clarified wastewater sits in between. This wastewater is allowed to drain into an adjacent field and return to the local watershed. Naturally occurring bacteria breakdown the remaining solids (West Virginia University, n.d.).

Septic systems are relatively affordable, making them economically sustainably, especially when treating very large, low density areas. Regular flushing of the septic tank is required to keep the system in working order. Leaks can be difficult to detect as the entire system is beneath ground level. Untreated runoff draining into the local watershed can potentially cause public and environmental health concerns. These concerns can lessen the environmental and social sustainability of such a waste treatment system. This being said, septic tanks are a very popular waste treatment system in rural areas with low density, and they are much more affordable than the installation of a larger sewage system which would require the installation of miles of piping, disrupting the environment in the process.

Reuse

There are two main byproducts of traditional sewage treatment: solids and water. Treated waste can safely be reused as fertilizer. Because of this, many wastewater treatment plants will sell their treated waste, diverting it from the landfill, both an economic and environmentally sustainable strategy.

Black water is often treated to a higher standard than drinking water due to safety concerns. Because of this, some systems will return the treated wastewater directly to a district's tap. Due to social stigmas however, this is often not a socially sustainable or feasible option. Instead, treated water is often either returned to the drinking water source (e.g. injected into underlying aquifer or piped into the local reservoir) for a second round of treatment before returning to the tap, or simply poured into the local waste-receiving body of water (e.g. river or ocean).

Compost/Fertilizer

Composting human waste is a non-traditional but effective form of waste treatment. This strategy works much better for small districts than large districts, as the process is slower and more manually intensive, and thus better suited to handle lesser amounts of waste. Human waste composting systems generally treat liquid and solid waste separately, diverting urine for direct use as fertilizer, while maintaining solid waste for further treatment. Solid waste is often treated either directly through the use of composting toilets, or through a larger humanure system. Composting toilets utilize anaerobic bacteria and continuous ventilation to dry and treat human waste. Humanure composting systems require active pathogen testing, constant temperatures of 106° F and above, and a tightly sealed system to prevent waste leaks into the local groundwater system. Each produce a usable fertilizer, but monitoring and active participation by users is a necessary part of the process.

Economically, this method of waste treatment is extremely affordable, as it requires minimal infrastructure. Environmentally, this strategy is sustainable (if composting systems are properly monitored for leaks) as it is a direct one to one fertilizer production method with low embodied carbon and minimal risks involved due to its size and ease of monitoring. Social sustainability is where this method suffers, as due to the required levels of system interaction and the social stigma regarding human waste treatment, most people are unwilling to participate in such a system. A further challenge faced by this waste treatment strategy is the lack of regulatory code. Many regions have no laws governing the legality and sanitation of such systems, making legal installation a gray area.

Gray Water Treatment

Historically, gray water is treated simultaneously with black water. Certain systems however, such as black water reuse systems, require it to be treated separately. In this case, gray water treatment is often combined with stormwater treatment. Arguments for and descriptions of the two strategies are as follows. See the "Black Water Treatment" and "Stormwater Treatment" sections for further detail.

Black Water Combination

This is the most common method of gray water treatment. In this strategy, gray water drains directly into the sewer system, and then either to a combined or separate sanitary sewer system for treatment. The pollutants carried by this gray water are extremely versatile, as they contain a wide range of chemicals from hygiene products of all forms. These chemicals are very different from the toxins addressed through solid waste treatment and are less potent of a concern. Because of this, gray water is

treated through the same process as waste water, but the specific toxins contained within are often never directly addressed.

Non-potable Reuse

Similar to stormwater reuse, gray water can be reused for non-potable purposes, such as irrigation, toilet flushing, or heating/cooling systems. If full treatment of contained toxins is desired, active participation of those producing the gray water to use only biodegradable hygiene products is required. This active participation can slightly lessen the social sustainability of such a treatment system, as it can be considered less desirable than potential alternatives. There is very minimal effort to participate however, so this negative impact is not substantial. This strategy lessens a district's impact on waste treatment facilities and the demand for fresh sources of water for non-potable needs, making it environmentally sustainable. This strategy does contain within it the potential to release untreated toxins into the environment through irrigation, however, which is not environmentally sustainable. The lessened need for fresh water for non-potable needs carries with it the opportunity to save money, increasing the economic sustainability of this strategy. This can be negated by the cost of retrofitting an existing structure with the necessary infrastructure to allow non-potable reuse for sources such as heating/cooling and toilet flushing. In all, gray water reuse can be sustainable or not depending on how it is executed. See the "Stormwater Reuse" section for further discussion.

Cooling/Heating Systems

Most buildings require some level of temperature control to keep residents comfortable. The demand for heating and cooling varies greatly depending on environmental location and building use. For example, colder climates require more heating, while hotter climates require more cooling. Commercial and industrial buildings produce large amounts of heat, and thus require its removal to maintain comfortable temperature for the workers. Residential buildings often require large amounts of heating, and relatively little cooling. This relationship can easily be utilized within district design, as heat from commercial/industrial spaces can be removed and transferred to residential spaces as needed. Heating and cooling demands are some of the largest energetic demands of a building. Strategically addressing these systems can greatly reduce a building or district's energy consumption, raising its economic and environmental sustainability.

Ventilation is another system which is often linked to heating and cooling systems. This is because ventilation systems can either remove or deposit heat as they replace stale air with fresh air. Ventilation can be forced and built into a heat distribution system, or passively designed into a building's architecture. Though ventilation is not thoroughly described in this thesis, it is an important component to heat distribution within a space, and ensures that a space is healthy to reside in. No district scale ventilation systems exist, as this is purely a building to building concern. It should be noted however that ventilation systems are intricately linked to the heating and cooling needs of all buildings, and thus the heating and cooling needs of any district.

The method through which heat is distributed through a building has a significant impact on how it is experienced. All substances are heated best through direct contact with another heated material, thus it is much more efficient to heat humans through radiant heating in floors or walls than through blowing hot air while the floors and walls remain cool.

Electrical HVAC

Many cooling and heating systems in modern homes are simple electrical driven heating units, which deposit or remove heat from air and vent this air throughout the building. These are relatively inefficient systems as they treat the entire building at once, regardless of where specific heating needs are. Air is also a very inefficient media for heat transfer, which does not lend well to this strategy. HVAC systems consume most of the electricity required within a building. This low efficiency requires much higher power consumption, which depending on the electrical source, can be very costly, and thus economically unsustainable. The amount of additional required duct work to install an HVAC system is rather large as well, requiring a large initial investment with inefficient results. The amount of required material and power consumption needed in these systems also makes them environmentally unsustainable. They are the current standard in many modern American buildings however due to building tradition.

Cogeneration

Cogeneration, also referred to as combined heat and power (CHP), “is the simultaneous production of electricity and heat, both of which are used” (Cogeneration Europe, n.d.). Often, cogeneration productions involve the capturing of waste heat from energy production or waste treatment plants. This method of heat production is not a heat distribution technique, as many of the other strategies described here, but instead one of heat production. As cogeneration requires a facility to produce large amounts of waste heat during energy production. This is not a feasible strategy for all districts as determined by their electricity source. This especially is not a feasible strategy for micro districts who are unable to host a large electrical production or waste treatment facility due to their size. As cogeneration involves the harnessing of a waste product, it is both economically and environmentally sustainable. The social sustainability of this strategy depends on the production process of the waste heat, and the associated emissions effect on public health. Waste heat can be collected through a water system and used for radiant heating methods, or through a ducting system and used to power HVAC systems. This later method is highly inefficient, and is thus rarely done.

Water Loop Heat Pumps

Water loop heat pumps are closed loop systems through which water is pumped, exchanging heat with spaces as it passes. This allows for efficient redistribution of heat around a building or district, using radiant heat techniques. The system runs chilled water through hot spaces to remove heat from them. The captured heat is redistributed to spaces which require heating, thus cooling the water once more. These systems are highly flexible, highly efficient, and require low levels of maintenance compared to individual HVAC systems in each building. Water loop heat pump systems require a variety of uses and temperature demands to operate at full efficiency. This makes them excellent systems for mixed use districts. This is because commercial and industrial spaces produce excess heat, while residential spaces require heat. Water loop heat pumps allow for cheap and efficient redistribution of excess heat from where it is to where it is needed.

Water loop heat pump systems are scalable for a wide range of district scale sizes. From large single multi-use buildings, such as single live/work apartment complexes, to a multi-neighborhood district, this strategy can be sized to address a wide variety of needs. These systems are especially popular in campus size districts. This is because wider variety in building usage among the district increases their efficiency. Another reason is that as the initial investment for such a system can be very substantial, and the larger

the served district is, the more economically feasible the system is to implement. Due to their high level of efficiency, water loop heat pump systems are both environmentally and economically sustainable. The lack of emissions produced in the heating process makes these systems both environmentally and socially sustainable. These systems are also much smaller than traditional HVAC systems, and are easier to incorporate into building designs using less equipment. This lowers the amount of materials and embodied carbon required, raising their environmental and economic sustainability. They also require less maintenance than traditional HVAC systems, raising their social sustainability.

Ground/Water Coupled Heat Exchange

Ground and water coupled heat exchange harnesses a body of mass (either earth or water) for heat storage and exchange. During periods in which heat needs to be removed from the district, such as in the summer months, heat is deposited into these sites through the use of a water loop system. In the winter months, the heated mass deposits energy into the water loop, and that heat is then transferred throughout the district. These systems function similar to a closed water loop heat pump system, in that piped water is used to transfer heat throughout the district. In heat exchange systems however, a large body of mass is used as a storage tank for heat throughout the year, as opposed to the immediate distribution of water loops. These systems can only be combined with radiant heating methods rather than HVAC systems.

These systems are highly efficient, and produce no emissions in the process, increasing their economic, environmental and social sustainability. They do however require either a large body of land or water to function as the area for heat exchange. This can be economically prohibitive for smaller district projects. If the body of mass used for heat exchange is not an aquifer or completely separate from surface water bodies, thermal pollution can become an issue. This can lower the environmental sustainability of coupled heat exchange systems.

Passive

Passive heating and cooling is achieved through intelligent design of the buildings used within a district. This design technique involves the harnessing of solar heat, shading and natural ventilation using wind to heat, cool, and ventilate spaces. These systems often harness the thermal mass of the building material itself to heat slowly, remaining cool most of the day, and releasing the stored heat at night. To regulate internal temperatures, the sun must be allowed to enter, or be blocked at certain periods of the day during different times of year. Such designs can either be fully automated, a rather expensive strategy, or run through the active participation of residents opening and closing doors and blinds.

This strategy is applied building by building and can only function for a whole district if each building is designed for passive heating and cooling. Passive systems require significantly less materials to build, and instead intelligent and creative design. This greatly lowers their embodied carbon and allows them to produce no emissions, making them environmentally, economically and socially sustainable. These systems require user education and active participation to function properly however, which in a social climate used to being catered to by machines, can be difficult to properly manage. This strategy requires social change and participation to be fully socially sustainable.

Combustion

Combustion processes for heating refer to the burning of fuels, often wood, to produce heat inside of residential units. This method does not scale up any larger than single unit design and has no interconnection in district design. The efficiency of this method is determined by the combustion system and fuel choice. Most commonly, this is a wood burning stove and wood logs or pellets. Though minimal infrastructure installation is required, this is not a very efficient method of heating, and is therefore relatively unsustainable economically. The efficiency can be improved however if the system is tied in to heat the thermal mass of the entire building rather than just the air. The emissions produced through combustion are determined by the fuel source used. As wood is the most common, and is not a very clean burning fuel, the emissions produced have a negative social and environmental impact on the surrounding community and ecosystem. As a whole, combustion is not a very sustainable heating method.

Combined Systems

Examples of combined infrastructure systems are few and far between. They most commonly appear in net zero energy district designs. This is due to their high level of efficiency and ability to transform waste products for one system into an energy source for another. District design is an excellent area to harness the benefits of combined infrastructure systems, as the infrastructure types are more varied and much larger than those required for single units. This size requirement is essential to ensure that enough waste product is produced to meet the demanded source. Few combined systems were found during research for this thesis, but presented examples are as follows:

Biogas/Waste Treatment

During black water treatment, methane is naturally produced. This methane can be cleaned and repurposed as biogas. Such systems can easily be integrated into preexisting natural gas piping networks. This process allows for the fluid transformation of a waste product into an energy source while reducing greenhouse gas emissions and a district's reliance on alternative power sources. The gas produced is relatively clean burning, continuing to increase the environmental and social sustainability of this system. The process of turning a waste product into an energy source is highly economically sustainable, as there is no cost beyond the initial capturing equipment. This infrastructure strategy requires a large waste treatment plant, and is therefore only viable for large districts treating their waste through traditional sewer treatment methods.

Heat/Waste Treatment

A second bi-product of black water treatment is heat. Like cogeneration, where waste heat from electricity production is repurposed as a heating source, this waste heat from black water treatment can be harnessed for heating purposes. This is similar to biogas production, but the energy produced is only used for heating purposes. The ability to capture a waste product and reuse it is both economically and environmentally sustainable. The lack of emissions produced during this process also allows this strategy to be socially sustainable, as it has no negative impact on public health.

Applied Retrofit Example

According to the Preservation Green Lab, "it can take up to 80 years for a new energy efficient building to overcome, through efficient operations, the climate change impacts created by its construction". This means that to move forward with sustainable city and district design, it is important to focus on

retrofitting existing infrastructure to improve it, rather than only making something new. Part of the aim of this thesis is to provide a comparative framework of various infrastructure types that can be applied to choose an appropriate retrofit strategy to improve a district's sustainability. Existing districts are more limited than new projects regarding which systems can be appropriately integrated into their design. Existing conditions must always be considered in the design process. In retrofit design the number of existing conditions to consider is magnified and is therefore a trickier and more complex puzzle.

In an effort to show how the contents of this thesis can be applied to aid in a district retrofit design, one studied site was chosen as an example: Hassalo on 8th. This four-block district has a well-integrated water treatment system, which allows for the capture of stormwater, gray water, and black water and their reuse. The efforts taken to design the site in its current state were driven largely by economic sustainability goals. High prices for sewer access allowed the site to easily make the economic decision to design an onsite all-in-one water treatment plant called NORM. This living machine both reduces the site's reliance on exterior water sources as well as the amount of onsite water returning to the Portland combined sewer system. The design strategy implemented on this site is one of the first and most innovative decentralized water treatment strategies in the United States.

Using the options and considerations described throughout this thesis, it becomes apparent that there are a few areas where this district design could have been improved however. These are through electricity generation, capturing of waste heat, thermal storage, thermal transportation, and social sustainability strategies. Hassalo on 8th relies on electricity supplied through the City of Portland's power grid. Majority of this power comes from Bonneville dam, a hydroelectric dam. The Columbia Basin, where Bonneville dam resides, has a bountiful water supply most years, resulting in a continuous supply of water, and thusly cheap, emission free power. In a theoretical future scenario where drought strikes the Columbia Basin, heavily impacting the Columbia River, this power source has the potential to become significantly more expensive. In this case, it would be economically advantageous for Hassalo on 8th to consider installing an electrical source onsite.

Hassalo on 8th consists of four blocks of densely populated, extremely tall buildings with small footprints. This means that there is not enough space to adequately provide enough electricity through pure solar or wind generation systems. The site is not situated in the correct setting to harness geothermal energy either. As Portland is located within a seismic region, there is no proper burial location nearby to deposit nuclear waste, making nuclear energy a nonlogical option. As described in the "Electricity" section of this thesis, the only other available options are combustion and fuel cells. As fuel cells can be significantly smaller and more efficient than combustion systems, this is the recommended strategy for electrical production onsite. There are a variety of fuel options to choose from, and this will be discussed in greater detail later in this section.

Hassalo on 8th has the benefit of containing both commercial and residential buildings as well as a waste treatment plant onsite. Both the commercial buildings and waste treatment plant are potential sources of heat production, a resource which the residential buildings need. This makes Hassalo on 8th an excellent option for heat capture and redistribution, which can easily be done with a closed loop water heat pump system. As residential heating needs vary greatly throughout the year, it is also advisable to create a thermal storage system. The site is not overlaying an aquifer, and therefore must either harness the use of a massive water tank or the earth to hold heat until it is needed.

A second wasted resource produced onsite is methane, which can easily be transformed into biogas. This resource is naturally produced during all black water treatment processes. As Hassalo on 8th is home to a beautiful waste treatment system, it is also home to a small methane factory. This system has the potential to be transformed into a biogas production facility. This biogas could either be used to power fuel cells and kitchen appliances onsite or connected into the preexisting natural gas piping network and sold at a profit. In order to allow for the gradual retrofit of such an in-depth system, fuel cells onsite could be chosen to be powered by natural gas. Natural gas and biogas are easily substituted for one another, as they differ primarily only in production source and have very similar molecular makeups.

Another component of district design that could be improved in the Hassalo on 8th district are the strategies used to address social sustainability. This could be done through the addition of sharing programs and facilities and/or community projects such as a garden. Examples of potential sharing programs include vehicle or meal sharing programs, or a district wide “share room” for residential and office supplies. None of the units onsite are designed to be affordable housing, and these strategies would potentially increase the affordability of living within the district. They would also help to foster a sense of communal support among district residents and workers. This socially sustainable sentiment could be furthered through the introduction of a communal gardening space in the district. Here residents could work together to teach and work alongside one another to raise food and ornamentals. The social and economic sustainability of Hassalo on 8th are two areas which could greatly be improved, as it is currently inaccessible to many socio-economic groups with minimal encouragement of district community.

The retrofits described in this example may be cost prohibitive, but it is important to consider two points. The first being that retrofits should often be done continuously and incrementally. As knowledge and experience continue to increase, new implementable retrofit strategies will continue to present themselves. Aging systems must be repaired and can often be greatly improved in the process. Limitations on these improvements are often controlled by the perceived cost barrier, which ties into the second point: many sustainable infrastructure strategies are disregarded as the price for each nontraditional system adds up and appears to be economically unsustainable. There is a point however when the addition and integration of these systems becomes cheaper and more efficient than traditional ones. For example, if a building is designed to be completely passive with automated temperature control systems, this can allow for the complete removal of the HVAC system. The amount of money saved by removing the HVAC system can be more than the additional cost in smart design time and the monitoring system required to run the building.

This same principle applies to district design. It can be economically prohibitive to simply install fuel cells to power a district, or a waste treatment facility. However, if an entire integrated system is installed where waste products are used to power other infrastructure systems, suddenly the whole system begins to pay for itself. This is called “tunneling through the cost barrier”. Due to traditional ways of thinking and risk averse practices, this is often not done. In order to face the challenges cities around the world are beginning to see however, the world requires innovative design. This is an impossible feat without designers willing to take the plunge and tunnel through the cost barrier with creative holistic district designs.

This type of nontraditional design thinking was available to the master planners of Hassalo on 8th due in part to the fact that the space was able to be designed under one owner. The required infrastructure to

treat all the waste water produced in the new buildings onsite would have been much more difficult to install if the site had been owned by multiple individuals. This also means that the site is a perfect candidate for some of the larger district systems described in this retrofit example, such as the closed loop water heat pump. Ownership can severely limit or enhance the retrofit options available to a district, and Hassalo on 8th is currently benefitting from the positive end of this spectrum.

Conclusion

As discussed throughout this thesis, different infrastructure systems are optimized at different scales. Most of these systems are optimized in between the macro or city scale, and the scale of individual units. It is uncommon in the US to see these systems implemented at a district scale, however. The barriers preventing their implementation are primarily related to both ownership and policy limitations, as well as to social norms and expectations.

Barriers related to ownership present themselves as district designs seek to introduce multi-block infrastructure systems. Unless all of the land used in the district design is owned by one owner, as in the case of Hassalo on 8th, it can be extremely difficult to engage and involve all land owners towards one goal. An example of these limitations can be seen in the Brewery Blocks project. The chiller system used is designed to serve one third of the Portland downtown. Due to lack of ownership however, the necessary piping to provide cooling services has only been installed in a small portion of this area. The chiller currently operates at only 10% of its capacity. This is because the designers do not own one third of the Portland downtown, and not enough building owners have not desired to pay the retrofit costs or allow construction beneath their buildings. It is possible, if the city of Portland were to collaborate with the system designers that as road maintenance projects took place in downtown Portland, so the necessary pipeline could be installed underneath. This collaboration is not currently happening however, and there is no organization or driving force in place to make it happen.

Barriers related to policy include primarily zoning limitations. As experienced in the Going Street Commons, zoning policy limited the allowable density of the project, as well as charged a high number of fees to allow for the non-traditional redesign of the site. These extra fees significantly raised the price of the project, increasing the financial burden on the master planners, and consequently on the future residents. The density limitations related to the zoning laws prevented the addition of units to spread out this financial burden. This decreased the potential for affordable units and their contribution to the diversity and social/economic sustainability goals of the district. Additional policy barriers involve the lack of regulation over such systems including water reuse, decentralized waste treatment, onsite electrical production and net metering. Without regulation, it is extremely difficult to legally implement new technologies and strategies in these areas.

Social barriers preventing district design primarily involve the social norms dictating when the sharing of amenities is appropriate, and when it is not. This social stigma towards the sharing of centralized amenities as an “inferior” practice places all district designs implementing centralized amenities at risk of devaluing their project. Another social norm preventing efficient district design is that building occupants are accustomed to not interacting with infrastructure systems. This places an emphasis on automated systems, which can be less efficient and require excess materials to build and energy to operate. These social stigmas force the perpetuation of unsustainable and less efficient practices.

In order to overcome these social barriers, it is important that comfortable examples of such systems become more common. This cannot happen until the policy and especially the ownership barriers are addressed. Examples to address these issues can be found only by looking to other countries who have developed legal strategies to allow for this type of construction.

Many countries in Northern Europe have developed methods to implement district design strategies, as it aligns well with the sustainability goals of these countries. In these locations, policy governing the use of decentralized waste treatment, water reuse, and onsite electrical production allow for clear steps towards legal implementation of these systems. Socially, these societies accept the sharing of amenities and infrastructure interaction, allowing more efficient and sustainable design to be accepted as the norm. Japan has developed a method to overcome the ownership barriers associated with district design, allowing for the collaboration between government and private owners to implement district scale retrofits.

This thesis began with the goal to create a comparative chart of infrastructure systems, analyzing their sustainability with regards to the triple bottom line and the proper scale at which to implement them. As research progressed, it became apparent that the data to compare these systems quantitatively is not readily available. To properly create this comparative chart, quantitative studies still need to be completed. This quantitative research requires engineers to consider with greater importance the efficiency and ability to implement district scale systems. The US is not home to enough of these systems for proper analysis within the states. This requires consideration of global knowledge of district design, something which is severely lacking within the US.

As the author of this thesis, I propose a mass study of district scale systems currently implemented around the world. Use of district design and integrated infrastructure will increase as its ease of implementation and understanding does. If enough research could be done to create a comparative chart presenting a scale range for each system described in this thesis, and potential systems they could be integrated with, the ease of integrating these systems into a district design would be vastly improved. This scale range needs to be created using quantitative data presented as a range of system efficiency vs. size. Ideally this size could be analyzed in three ways, through physical area, number of users, and population density. This would create more in-depth knowledge of how these systems function within a district, and the relative importance of these three parameters. I hypothesize that though related, each will be limiting in its own right, and thus all three must be considered when selecting appropriate systems.

The research completed for this thesis was able to present clear conclusions towards the barriers preventing district scale infrastructure implementation in the US, which are primarily ownership and policy driven. Once again, examples of overcoming these barriers are found around the world. In a future project, more in depth research into these topic could present some very useful insight with regards to district scale infrastructure implementation.

Works Cited

(n.d.). *Going Street Commons*, Birdsmouth Construction, <<https://www.goingstreetcommons.com/>> (May 17, 2018).

“Average Quality of Fossil Fuel Receipts for the Electric Power Industry.” (2016). *U.S. Energy Information Administration (EIA)*, chart, EIA.

“The Brewery Blocks in Portland's Pearl District.” (n.d.). *The Brewery Blocks - In Portland's Pearl District*, <<http://www.breweryblocks.com/>> (May 17, 2018).

Dr. Eric Brymer, Thomas F. Cuddihy & Vinathe Sharma-Brymer (2012) The Role of Nature-Based Experiences in the Development and Maintenance of Wellness, *Asia-Pacific Journal of Health, Sport and Physical Education*, 1:2, 21-27, DOI: 10.1080/18377122.2010.9730328

“Campus Energy Loop.” (n.d.). *Portland State University*, <<https://www.pdx.edu/sustainability/campus-energy-loop>> (May 18, 2018).

City of Malmo. “Vastra Hamnen/The Bo01 Area: A city for people and the environment.” *City of Malmo*. (2006)

“Code of Ethics.” (2017). American Society of Civil Engineers.

“What is a Fuel Cell.” (n.d.). *What is a Fuel Cell?*, The Canadian Hydrogen and Fuel Cell Association (CHFCA), <<http://www.chfca.ca/education-centre/what-is-a-fuel-cell/>> (May 18, 2018).

(n.d.). “What is Cogeneration.” *Cogen Europe*, Cogen Europe, <<https://www.cogeneurope.eu/knowledge-centre/what-is-cogeneration>> (May 18, 2018).

“Combined Sewer Overflow Control (Big Pipe Project).” (n.d.). *Environmental Services*, The City of Portland Oregon, <<https://www.portlandoregon.gov/bes/31030>> (May 17, 2018).

The Data Team. (2017). “Weather-related disasters are increasing.” *The Economist*, The Economist Group Limited.

“How much carbon dioxide is produced when different fuels are burned?” (2017). *EIA*, U.S. Energy Information Administration (EIA), <<https://www.eia.gov/tools/faqs/faq.php?id=73&t=11>> (May 18, 2018).

“Electricity Production and Distribution.” (n.d.). *Alternative Fuels Data Center*, U.S. Department of Energy, <https://www.afdc.energy.gov/fuels/electricity_production.html> (May 17, 2018).

Environmental Services. City of Portland. (2016). *Stormwater Management Manual*.

“FAQs - Is uranium radioactive?” (n.d.). *DUF6 Storage*, <<http://web.ead.anl.gov/uranium/faq/uproperties/faq5.cfm>> (May 17, 2018).

Foletta, N., and Fields, S. (n.d.). *Europe's Vibrant New Lox Car(bon) Communities*. *Europe's Vibrant New Lox Car(bon) Communities*, rep., 1–116.

Forsberg, C. W. (1997). *Description of the Canadian Particulate-Fill Waste-Package (WP) System for Spent-Nuclear Fuel (SNF) and its Applicability to Light-Water Reactor SNF WP with Depleted Uranium-*

Dioxide Fill. Description of the Canadian Particulate-Fill Waste-Package (WP) System for Spent-Nuclear Fuel (SNF) and its Applicability to Light-Water Reactor SNF WP with Depleted Uranium-Dioxide Fill, rep., Oak Ridge National Laboratory, Oak Ridge, Tennessee.

GBD Architects Incorporated. (n.d.). "Hassalo on Eighth." *Hassalo on Eighth*, GBD, Portland, OR.

Gonzalez, M. T., and Kirkevold, M. (2013). "Benefits of sensory garden and horticultural activities in dementia care: a modified scoping review." *Journal of Clinical Nursing*, 23(19-20), 2698–2715.

"Hammarby Sjöstad, Stockholm, Sweden | Urban green-blue grids." (2016). *Urban green-blue grids for sustainable and resilient cities*, Urban Green-Blue Grids, <<http://www.urbangreenbluegrids.com/projects/hammarby-sjostad-stockholm-sweden/>> (May 17, 2018).

Holt-Lunstad, Julianne, Smith, Timothy B., Baker, Mark, Harris, Tyler, Stephenson, David. (2015) "Loneliness and Social Isolation as Risk Factors for Mortality: A Meta-Analytic Review." *Perspectives on Psychological Science*

"Home." (n.d.). *Kailash Ecovillage*, <<http://www.kailashecovillage.org/>> (May 17, 2018).

"Kenton Women's Village FAQ." (n.d.). *Historic Kenton*, Kenton Neighborhood Association, <<http://historickenton.com/village/>> (May 17, 2018).

Legese Feyisa, G., Dons, K., and Meilby, H. (2013). "Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa." *Landscape and Urban Planning*, 123, 87–95.

Luederitz, Christopher, Lang, Daniel J., Von Wehrden, Henrik. "A systematic review of guiding principles for sustainable urban neighborhood development." *Landscape and Urban Planning* 118 (2013): 40-52. Print.

McCamant, Kathryn, Durrett, Charles. *Creating Cohousing: Building Sustainable Communities* (2011) (2014). Mobile Maplets, Zaia Design, <<https://www.mobilemaplets.com/showplace/4981>> (Jun. 11, 2018).

Monroe, A., Loux, Jeff, Haynes, Bruce, & Wheeler, Stephen. (2012). *Social Equity and EcoDistrict Development: Best Practices In Northern Europe and North America*, ProQuest Dissertations and Theses.

"Municipal Wastewater." (2018). *EPA*, Environmental Protection Agency, <<https://www.epa.gov/npdes/municipal-wastewater>> (May 17, 2018).

Nobis C (1999) Neue Mobilität. Chapter 5 in Sperling (1999, Ed) *Nachhaltige Stadtentwicklung beginnt im Quartier*. Forum Vauban, Freiburg (pp 201-262)

Patail, M. (2017). "How a Portland-Wide Collaboration Helped Shelter Homeless Women." *Portland Monthly*, Portland Monthly, <<https://www.pdxmonthly.com/articles/2017/10/16/how-a-portland-wide-collaboration-helped-shelter-homeless-women>> (Jun. 12, 2018).

Peterson, K. (2018). *Backdoor Revolution - The Definitive Guide to ADU Development*. Accessory Dwelling Strategies LCC, Portland, OR.

**“Portland State University – Campus Loop Phase 1.” (2016). *JH Kelly*,
<<https://www.jhkelly.com/project/portland-state-university-campus-loop-phase-1/>> (May 18, 2018).**

Preservation Green Lab: National Trust for Historic Preservation. “The Greenest Building: Quantifying the Environmental Value of Building Reuse”. (2016)

Rieselfeld Projekt Group (RPG). “The New District of Freiburg-Rieselfeld: A case study of successful, sustainable urban development.” *City of Freiburg*. (January 2009)

Scheuer, J. and Newman, P. “Vauban: A European Model Bridging the Green and Brown Agendas.” *Global Report on Human Settlements*. UN Habitat (2009)

Söderback, I., Söderström, M., and Schäländer, E. (2009). “Horticultural therapy: the ‘healing garden’ and gardening in rehabilitation measures at Danderyd hospital rehabilitation clinic, Sweden.” *Pediatric Rehabilitation*, 7(4), 245–260.

**“What is a septic system? How do I maintain one?” (n.d.). Tech Brief Fact Sheets - Drinking Water, West Virginia University - National Environmental Services Center,
<http://www.nesc.wvu.edu/subpages/septic_defined.cfm> (May 17, 2018).**

Winter, M. J. (n.d.). “Human Waste Treatment and Water Reuse at Hassalo on Eighth.” Northwest EcoBuilding Guild, <<http://www.ecobuilding.org/code-innovations/case-studies/human-waste-treatment-and-water-reuse-at-hassalo-on-eighth>> (Jun. 12, 2018).

Appendix A

The relevant professionals interviewed as part of research for this thesis are as follows:

Kyle Anderson of GBD Architects:

Anderson is a Design Principle at GBD Architects with over 23 years of experience. He was actively involved in the designing of the Hassalo on 8th project, and he granted me both an interview and site tour.

Bruce Brown of GBD Architects:

Brown is both a principle and the Quality Assurance and Risk Manager for GBD Architects and has been working therefore over 30 years. He is familiar with the details of the Brewery Blocks and granted me an interview and a tour into the specifics of the project and the site. The office of GBD Architects ties into the Brewery Blocks heating and cooling system.

Charles Kelley of ZGF Architects:

Kelley is a senior architect and urban planner with over 32 years of experience. He has had the privilege to work on multiple district design projects over his career. Kelley allowed me to interview him about district design and applicable strategies.

Jonathan Lundstrom of Birdsmouth Construction:

Jonathan Lundstrom is an Architect at Birdsmouth Construction. He worked to help design the Going Street Commons. He gave me a thorough interview about both the site and district design challenges and strategies.

Pandora Patterson of Kailash Ecovillage:

Patterson is an Assistant Manager at Kailash Ecovillage. She has been living within the community for years and has an intricate knowledge of the community and how it functions. She granted me both an interview and a very detailed site tour.

Joanna Tran of Catholic Charities Oregon:

Tran is a Housing Program Coordinator for Catholic Charities Oregon. Catholic Charities Oregon has multiple housing projects aiming to alleviate homelessness. One of these sites is the Kenton Women's Village. Tran gave me an interview discussing the specifics of the site and how it functions.