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Heat and Light in the City of the Future: A Feasibility Study of Renewable Energy in Lewiston, Maine

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A Feasibility Study of Renewable Energy in Lewiston, Maine

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List of Abbreviations

AC: Alternating current.

ASHP: Air-source heat pump.

BPT: Break pressure tank.

BTU: British thermal unit.

CHP: Conduit Hydropower.

DC: Direct current.

EIA: U.S. Energy Information Administration.

EV: Electric vehicle.

FERC: U.S. Federal Energy Regulatory Commission.

GHG: Greenhouse gas.

GW: Gigawatt.

kWh: Kilowatt hour.

LCOE: Levelized cost of energy.

MHP: Microhydropower.

MW: Megawatt.

PRV: Pressure reducing valve.

PV: Solar photovoltaic.

RFO: Renewable fuel oil.

WSS: Water supply system.

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Abstract

Urban energy systems are critical to mitigating and adapting to climate change. Cities demand massive amounts of both heat and electricity, but conventional methods of creating this energy release large amounts of pollutants and greenhouse gases into the atmosphere. Effectively addressing climate change requires that these energy systems be transitioned to low-carbon alternatives as quickly as possible. Hybrid distributed renewable energy systems can be implemented within the urban framework to produce local renewable energy efficiently and affordably. The proposed system, composed of multiple types of small renewable energy generators located around the city, provides significant reductions in energy cost and greenhouse gas emissions, increases the stability of the local electrical supply, hardens the grid to physical and cyber-attacks, and generates income for the city. This study identifies four types of renewable heat and energy generators suitable to the urban environment of Lewiston, a small city in central Maine. Solar, microhydropower, and conduit hydropower are considered for energy generation, and air-source heat pumps and electric resistance heaters are suggested as ways to sustainably produce heat. The hybrid distributed renewable energy system modeled in the paper can completely heat and power the city's residential buildings and more than cover our commercial electricity usage at a cost significantly lower than current energy prices and with 90% fewer greenhouse gas emissions than our baseline energy use. This paper proves that updating urban energy infrastructure is both a feasible and necessary step towards lowering energy costs and fighting climate change.

Introduction

According to the United Nations Framework Convention on Climate Change, the world has just 12 years to avert the most catastrophic impacts of climate change [1]. Cities, which house 54% of the global population, use massive amounts of resources and contribute significantly to global greenhouse gas emissions, are critical to the fight against climate change [2]. In order to ensure a livable future for all people, cities must take "urgent and unprecedented action" [1] to decarbonize their economies, transportation networks, building stock, and industrial sectors. This necessitates a dramatic shift in how fuels are sourced and used. In order to stave off the worst effects of climate change, renewable energy must be implemented to replace the burning of fossil fuels. Around the world, there have been at most two major energy transitions in human history – from wood to coal and from coal to natural gas – each of which took more than 50 years for a majority of people in the US to adopt the new form of energy to heat and light their homes and businesses [3]. This puts the required transition to renewable energy solidly in the 'unprecedented' category of climate action. Fortunately, the technology that will create the energy and the money that will facilitate the transition is currently available. The urgency with which society needs to adapt its energy systems requires thoughtful, system-scale planning in order to undertake the transition with maximum efficiency and minimal social impact. This paper assesses how one locality can implement renewable energy technologies and how the resulting network of generators intersects with social, political, and cultural issues, in order to facilitate a rapid and just transition to a low-carbon energy system.

This study models the transition to renewable energy in the city of Lewiston, a lower income former mill town on the banks of the Androscoggin River in central Maine. Its milling history left it with a network of canals throughout the downtown, which are now disused, and a number of massive industrial buildings that are in the process of being repurposed. These particular features offer great opportunities for renewable energy implementation. However, the decline of the mills, among other factors, left the city economically depressed. This study is grounded in the realities of Lewiston; 21.4% of the city's 36,000 residents live below the poverty line [4]. This city is primarily focused on economic survival, not longer-term problems like climate change. This is apparent in city planning documents, which focus exclusively on reducing the cost of electricity and heating fuels for residents and never on the emissions associated with that energy [5, 6]. In order to respect the practical concerns of the city and present a fuller picture of the impacts of the transition to renewable energy, the following analyses focus heavily on economic implications.

This paper specifically models the transition to a hybrid distributed renewable energy system. Hybrid denotes the fact that the system is composed of multiple types of energy generators, and distributed means that the generators are located throughout the city, not concentrated in one area like a traditional solar or wind farm. Combining multiple types of renewable energy generators with different strengths and weaknesses into a network provides many benefits beyond the environmental: it increases the stability of the electrical supply under all circumstances, hardens the grid to physical and cyberattacks, and increases the resilience of the grid to natural disasters [7-9]. Building a hybrid renewable energy system into the fabric of a city reduces transmission losses, increases the efficiency of the system as a whole, and allows citizens to have more control over their energy supply [9]. When combined into a network of generators around the city, these technologies have the potential to produce sustainable, stable, local power with little disruption to the cityscape.

In addition to electricity, energy used for heating is addressed in the project. This is to compensate for the fact that an inordinate amount of buildings in Maine use heating oil to stay warm throughout the state's long winters. The use of heating oil keeps the state's electricity consumption lower than most states – by shifting most of the burden of heating to fossil fuels. However, heating oil, which is analogous to diesel fuel, generates massive amounts of greenhouse gas and introduces health risks from toxic chemical spillage and exposure to fumes and exhaust. In order to truly model a sustainable energy system in Lewiston, different methods of heating must be considered. The following study produces a model of a city with all of its residences heated completely by electricity.

The siting of this study in Lewiston is important because existing literature on urban renewable energy tends to focus on wealthy mega-cities like New York City and Seoul; rarer are the studies of smaller, lower-income cities. Additionally, creating a framework for a transition to renewable energy in a city like Lewiston provides a better analog to more cities around the world than a study on somewhere like New York City. Hybrid distributed renewable energy systems by nature require that each network of generators is sized, sited, and composed of generating technologies that are chosen for that unique area in order to maximize generation potential and minimize environmental impact. However, though the model presented in the paper is created specifically for Lewiston, Maine, the fundamental ideas and underlying assumptions are applicable to any city. If we are to mitigate the impact of climate change, every city will have to transition to renewable energy.

The urgency of climate change and broad necessity of the subject matter informs the tone of this paper. The science is clear and the technologies have been invented; one of the last remaining hurdles to serious consideration of renewable energy on a local level is information. The quest to fully transition to renewable energy on the necessary timescale is often considered too ambitious, but this study and others prove that that is not the case. Much of this misunderstanding comes from a lack of understanding of the potential and limitations of renewable energy [10]. In order to bridge that divide and hopefully facilitate the fast and just implementation of renewable energy in Lewiston and beyond, this paper is written for policymakers and is intended to lay a foundation for the development of a local plan for the transition to renewable energy.

In order to assess the efficacy of a hybrid distributed renewable energy network in Lewiston, the paper first sets a baseline of current electricity and heating fuel use in the city and the economic and environmental impacts associated with that consumption. Then, four renewable energy technologies that are best suited to generating heat and electricity in Lewiston are introduced. The technologies selected all generate low-carbon electricity and heat, are currently available, and can operate in Lewiston's environmental, economic, and infrastructural context. The deployment of these technologies is then modeled within Lewiston to give an estimate of their total generation potential, installation cost, and the amount of greenhouse gas emissions they will avoid. Lastly, some potential barriers to implementation of the proposed renewable energy system are outlined and topics for further study are noted. The model created by the paper, which includes solar photovoltaic panels, two different hydropower generation strategies, and two types of electric heating methods, proves that producing all of Lewiston's energy needs from renewable resources found within the city is technically and economically feasible and environmentally imperative.

Chapter 1: Fuels and Emissions in Lewiston

In order to build something, you first have to know what you're working with. This chapter lays out Lewiston's baseline in terms of electricity and fossil fuel use in residential and commercial buildings and associated economic and environmental costs. No comprehensive studies of this type have been done in Lewiston before; the calculations rely on national and statewide data in order to estimate the city's current standing. This paper focuses on heating fuel and electricity usage, emissions, and cost for Lewiston's residential and commercial buildings. It does not include data for industrial buildings for two reasons: industrial fuel usage data is not commonly made public, and industrial settings offer different prospects for renewable energy than commercial and residential buildings (see Chapter 4 for a discussion of opportunities for industrial buildings). Industrial buildings tend to be much more energy intensive than other types of buildings; the average industrial client of Central Maine Power Company, the electrical utility that services the Lewiston area, uses 88% more electricity than the average residential customer [11]. However, in terms of building stock, most structures in the city are residential with commercial buildings a far second and industrial buildings comprising an even smaller percentage. Therefore, the following calculations necessarily underestimate Lewiston's total energy use but capture the heating fuel and electrical usage of the vast majority of buildings in the city. A detailed methodology of the calculations in this chapter can be found in Appendix C.

Chapter 1.1: Lewiston's Current Electricity, Gas, and Heating Oil Use

In 2017, Lewiston's homes and commercial buildings used just over 170,000,000 kWh[1] of electricity [11, 12]. This electricity use created 66,439 tonnes of greenhouse gas emissions.

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[1] A kilowatt hour, or kWh, is a measure of electricity used in one hour.

Maine uses significantly less electricity than most other states; the average American home uses 10,339 kWh of electricity per year compared to Maine's average of 6,612 kWh per year [13, 14]. Lewiston is no exception; homes in the city use an average of 6,643 kWh per year[2].

The reason for Maine's low electricity usage is that the majority of buildings in the state heat using oil, not natural gas or electricity as is common in most other states [13]. Census estimates report that 61% of Lewiston's residential buildings produce heat by burning #2 fuel oil, which is similar to diesel fuel [12]. Heating oil is delivered by truck to each building several times per winter and is kept in a tank in each home's basement, incurring thousands of dollars in fuel costs, delivery, and maintenance fees. In addition to clear economic and environmental concerns, which will be discussed in depth in the following sections, this heating method presents significant public health risks. Oil heating creates immediate safety concerns about spillage during both transportation and storage as well as increased danger during house fires. Fuel oil, even the low-sulfur mix required by Maine, produces sulfur dioxide when burned that contributes to air pollution and acid rain [15]. Because each house burns oil onsite, emissions are concentrated in residential and urban areas, increasing local air pollution and residents' probability of developing respiratory illnesses [16]. Though 70% of Maine homes are still heated with oil, residents are recognizing the problems created by heating oil and are rapidly switching to other forms of heat, particularly natural gas and wood pellets [17]. Propane heating has also gained in popularity in the past 10 years [12]. Wood pellets, depending on the source, can be environmentally friendly, but both natural gas and propane heating systems also face similar problems with cost, climate impact, and public health concerns as heating oil. Lewiston's heating fuels, as estimated by the 2017 American Community Survey, are given by Figure 1 [12].

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[2] See Table 10 in Appendix A for more information.

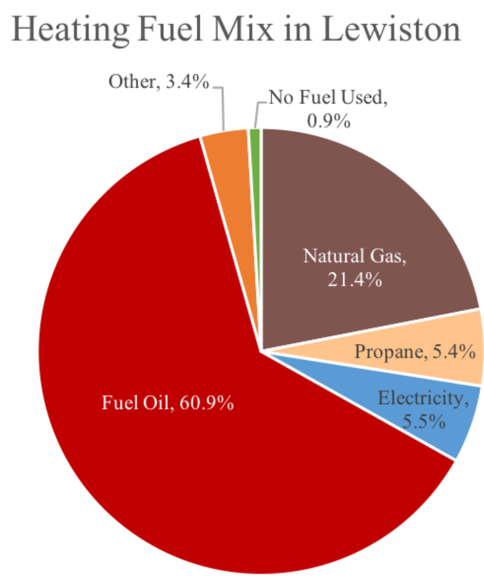

Figure 1: Heating fuels used in Lewiston by percentage of homes using the fuel [12].

Lewiston's homes consume millions of gallons of heating fuel per year. The estimated 9,782 homes burning fuel oil in Lewiston burned over 5 million gallons of oil in 2016 (see Table 1). Each house burned roughly 540 gallons of oil, which is in line with the Maine Governor's Energy Office's estimate for well-insulated, average size homes [17]. Table 1 provides usage estimates for measurable heating fuels; electricity used for heating is included in the previous table and the 3.4% of homes that heat using 'other' fuels cannot be accounted for.

For 2016	Number of Households	Average Use per Household	Total Use	Total CO_2e Emissions (tonnes)
Fuel Oil Users	9782	534 gal	5,226,000 gal	54,000
Propane Users	867	810 gal	703,000 gal	4000
Natural Gas Users	3437	71860 scf[3]	247,000,000 scf	13,000
Total				**71,000**

Table 1: Summary of heating fuel data. Fuel mix data from the census and other information from the EIA [12, 18].

[3] A scf is the most common unit of measure for natural gas. It represents one cubic foot of natural gas at 288.706 kelvin and 14.73 psi.

Chapter 1.2: Business as Usual Greenhouse Gas Emissions

Unlike its heating, Maine's electricity is generated mostly by renewable sources. As such, it is one of the states with the lowest total greenhouse gas (GHG) emissions from electricity generation (see Figure 2). In 2017, only 32% of all electricity produced in Maine came from nonrenewable sources; 30% from imported liquid natural gas, 1% from petroleum, and 1% from coal (see Figure 2). The state's complete lack of fossil fuel deposits, topography suitable to large hydroelectric projects, readily available wood byproducts for biomass burning, and adoption of a few large wind projects mean that the grid is relatively clean [13]. Make no mistake: Maine's grid is majority renewable in large part due to geophysical circumstances, not in response to any ecological imperative, legislation, or social incentive. It is important to note that, due to these circumstances, Maine's electricity generation fuel mix differs strongly from the broader context of electricity generation in New England, which relies primarily on natural gas and nuclear power (see Figure 3). Though it is impossible to source the electricity used in Lewiston to any particular location or generation method due to the complexity of the regional electrical grid, the calculations in this section assume that all electricity consumed in Lewiston is produced in Maine. This assumption is acceptable because the energy produced in Maine outweighs the electricity consumed in the state by a factor of 5 [11].

Maine's grid may be relatively green, but our neighboring states are still heavily dependent on fossil fuels. Further 'greening' Maine's grid by implementing more renewable energy projects will help alleviate greenhouse gas emissions across the entire region. It is absolutely critical that the worldwide emission of GHGs from fossil fuels be completely stopped within the next 30 years, or else we risk global catastrophe [1]. Every possible effort needs to be made to reduce GHG production from energy use, even in a state that started ahead of the rest.

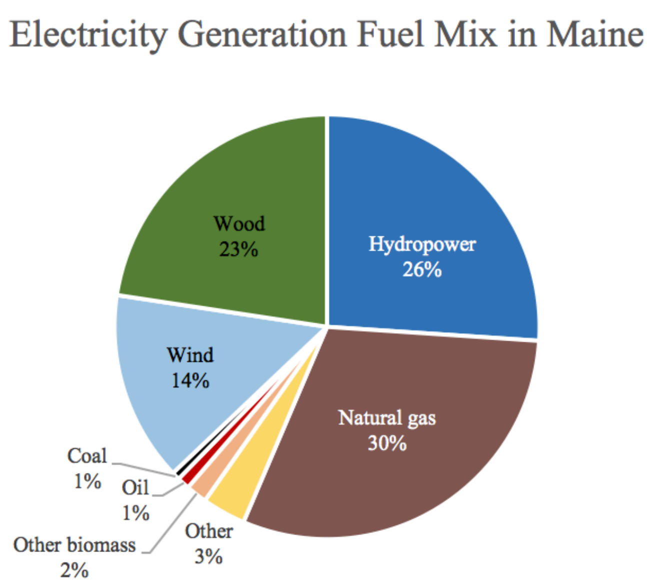

Figure 2: Fuels used to generate electricity in Maine in 2017 [13].

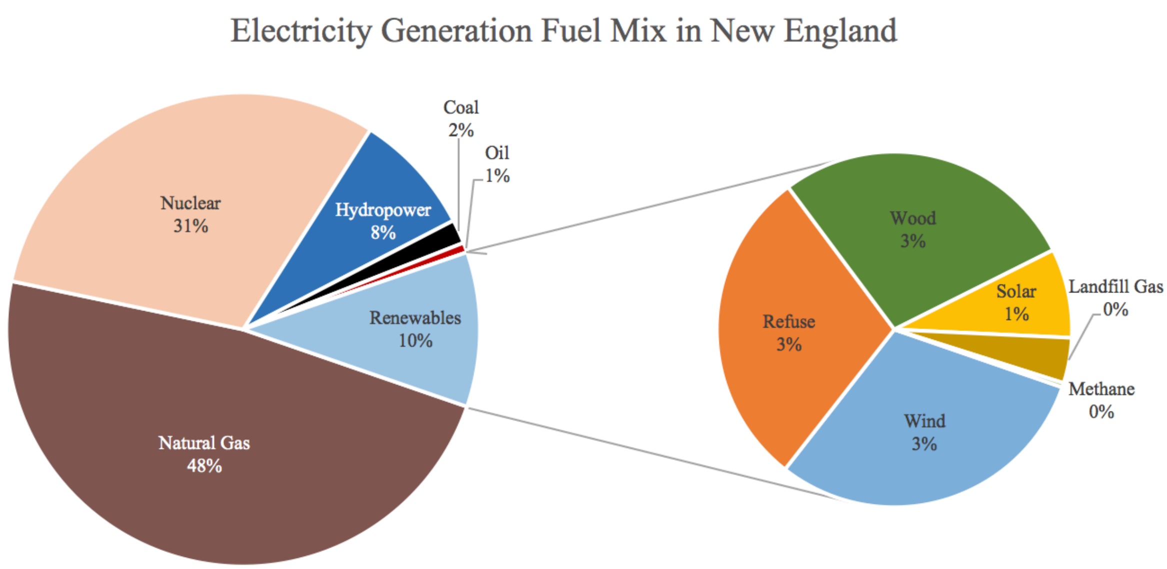

Figure 3: Fuels used to generate electricity in all New England in 2017 [19].

Electricity use only accounts for 37% of Lewiston's GHG emissions from residential sources[4]. Unsurprisingly, the majority of emissions in Lewiston come from burning fossil fuels

[4] See Figure 4 and Table 11 in Appendix A.

for heating. Fuel oil is the dirtiest, most GHG-intensive heating method; the 61% of Lewiston households that heat with fuel oil are responsible for the majority of emissions from heating (see Table 2). Of all fossil fuels, natural gas produces the least emissions to heat a comparable space. However, burning natural gas does still emit significant amounts of GHGs, which is unacceptable if we are to forestall the worst effects of climate change.

For 2017	Number of Homes	Total CO2e emissions (tonnes)	CO2e Emissions per Average House[5] (tonnes)
Oil Users	9782	53,600	5.48
Propane Users	867	4040	4.66
Natural Gas Users	3437	13,500	3.92

Table 2: Statistics on GHG emissions from residential heating in 2017 [12, 20].

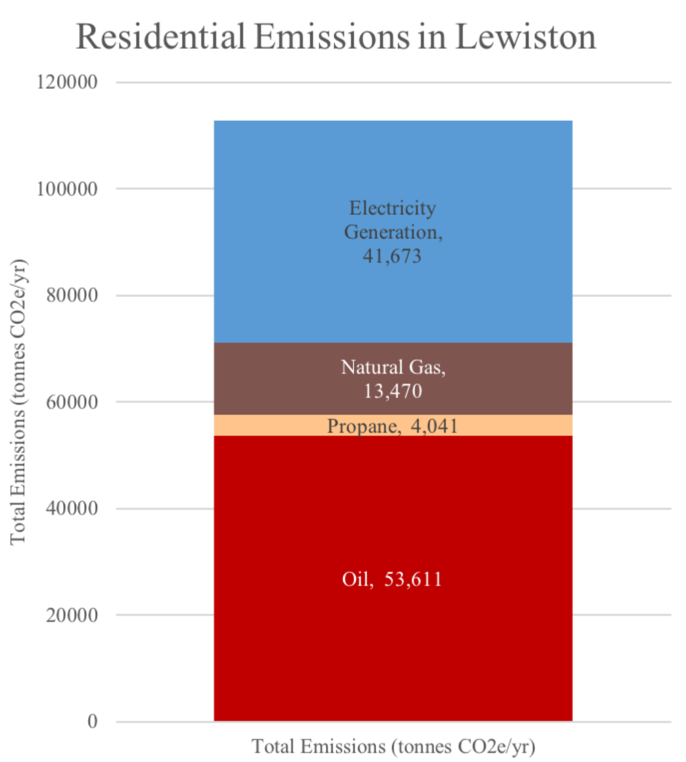

Figure 4: Residential GHG Emissions in Lewiston by source [12, 20, 21].

[5] Average house is defined as the amount of fuel needed to produce the heat created by burning Lewiston's average of 537 gallons of #2 fuel oil.

Chapter 1.3: Economic Implications

All of the energy consumption outlined in the past two chapters has a serious economic impact. Simply acquiring electricity to use and fuel to burn costs Lewiston's residents millions of dollars per year (see Table 3). Propane is by far the most expensive heating fuel, costing almost twice as much as fuel oil or natural gas [11, 13, 22]. Natural gas is the cheapest heating fuel. Electric heating is included in the electricity cost totals.

For 2017	Customer Type	Number of Customers	Average Price	Avg Bill per Customer ($/year)	Total Cost ($/year)
Electricity	Residential	16063	15.08 cents/kWh	$1,002	$16,100,000
	Commercial	2441	11.49 cents/kWh	$2,986	$7,300,000
	Total	**18504**	**13.29 cents/kWh**	**$1,994**	**$23,400,000**
Heating Fuel	Fuel Oil	9782	$2.66/gal	$1,420	$13,900,000
	Natural Gas	3437	$14.61/1000 scf	$1,050	$1,900,000
	Propane	867	$2.70/gal	$2,187	$3,600,000
	Total	**-**	**-**	**$1,540**	**$19,400,000**

Table 3: Summary of costs of electricity and heat in Lewiston in 2017 [11, 22, 23]

The emissions from burning fossil fuels to make electricity and heat for Lewiston also come with a significant cost that is not represented in the upfront price of energy. The social cost of carbon, as estimated in a 2015 study from Stanford University, is $220 per tonne of CO_2e [24]. The social cost of carbon quantifies the average economic damage associated with the emission of one tonne of GHGs. This number accounts for changes in agricultural productivity, property damage due to storms, healthcare costs from climate-related diseases and injuries, and changes in load on the energy system due to the warming caused by 1 tonne of CO_2e. Stanford's estimate of the social cost of carbon is much larger than the U.S. government's most recent accepted estimate of $40, which has not been updated since the current administration came into power on January 20, 2017 [25]. The Stanford number will be used throughout the rest of the paper; though it is dramatic, recent climate and social science support it over the more conservative U.S. figure. The Stanford number considers the impacts of climate change on GDP, stock markets, total factor productivity, and differences in developed versus developing countries' resilience to climate shock. Previous studies, including the EPA's estimate, assumed that these things were independent of climate change. Lived experience has shown that this is not true; economy and environment are intricately interrelated, meaning $220 per ton gives a better estimate of the true social cost of carbon equivalent emissions. The damages quantified in the social cost of carbon are not localized, as climate change is a global problem. This cost is levied on the entire world. In these terms, Lewiston's current energy use costs the world $30,000,000 every year (see Table 4).

For 2017	Total Emissions (tonnes CO_2e)	Total Cost ($)
Electricity	66,439	$ 14,600,000
Heating	71,122	$ 15,600,000
Total	137,560	$ 30,200,000

Table 4: Social costs of Lewiston's GHG emissions.

Chapter 2: Strategies for Hybrid Distributed Urban Energy Generation

This chapter outlines four types of distributed renewable energy and heat generation systems that are suitable for use in a cold, inland, riverfront urban setting like Lewiston: solar photovoltaic panels, micro-hydroelectric generators, in-pipe hydroelectric turbines, air-source heat pumps, and electric resistance heaters. Each of these technologies provides a relatively small amount of electricity or heat with minimal disruption to the local environment – which comprises both the ecosystem and the physical and aesthetic landscape of the area – when compared to large solar fields, wind farms, or traditional fossil fuel generators. The five technologies are meant to be implemented together as a hybrid renewable energy system. Each generates power or heat from a different source of energy and generates optimally under different circumstances, improving the resilience of the system and ensuring that Lewiston's resources are being used in the most efficient way possible.

Context is critical to understanding the potential presented below. These systems do not produce energy as reliably or as immediately as fossil fuel systems – this is not a reason to discount them but simply necessitates a more nuanced energy planning process. Solar photovoltaics' power output varies dramatically over time based on sunlight received by the panel. Microhydropower and in-pipe turbines' output varies based on the amount of water passing through them, though their generation is much more stable than that of photovoltaics. Air-source heat pumps actually don't produce electricity at all but use it to transfer energy to heat and cool rooms. The electricity they require varies based on the outside temperature. Altogether, this is a dynamic system that varies based on natural inputs instead of human will to a greater degree than traditional energy generation techniques. Adapting to this new energy regime will require social and infrastructural changes that are outlined in more detail in Chapter 4.

Just like a fossil fuel plant, it is important to remember that these systems are often not producing the maximum amount of electricity possible. This discrepancy is measured by the capacity factor, the ratio of average power produced to the system's maximum generation potential. Efficiency is another important metric for assessing renewable energy, as it captures the amount of energy produced compared to the total amount of energy available to be captured by that system. For heating systems, this is called the coefficient of performance (COP) and relates the amount of heat transferred compared to the amount of power used. Most power outputs are presented in kilowatts, a measure of electrical energy, or kilowatt hours (kWh), electrical energy produced or consumed per hour. For context, the average American household consumes 1.25 kW at any given time, which, times 24 hours, equals 30 kWh consumed per day [26]. Central Maine Power's average residential customer consumes only 18 kWh per day [11]. Costs of energy systems are compared based on the levelized cost of energy (LCOE), a measure of the total cost of the system over its lifetime, including installation and maintenance, divided by its total expected power production over the same period [27]. Because renewable energy generators require no fuel, the power requires no additional cost to produce and therefore eventually balances out the installation and maintenance costs, which are often higher than those of fossil fuel generators. This balance is captured in the payoff period, which is the number of years after installation at which the savings from the energy produced overtake the cost of installing and maintaining the system. This is also the time at which the system starts making money for the owner. Together, these metrics provide an understanding of the relative output and cost of each technology and allow for comparison against traditional fossil fuel-powered electricity and heat generators. They are not presented in this paper to provide a basis for comparison amongst the renewable technologies, as they are all intended to be implemented together in order to best utilize the renewable resources present the area at the lowest cost. Table 5 provides a summary of these metrics for each of the technologies, while Table 6 provides fossil fuel metrics for comparison.

	PV	MHP	Conduit	ASHP
Generation Potential Per Unit	1kW/6m^2	5-3000 kW	50 kW/turbine	N/A
LCOE	\$0.09/kWh	\$0.02-\$0.27/kWh	\$0.05-\$0.12/kWh	\$1.10-\$1.80/therm[6]
Payoff Period	10-20 years	10-20 years	10-20 years	4-7 years
Capacity Factor	<10%	>50%	>50%	N/A
Efficiency[7]/COP	15-26.6%	70-90%	70-90%	200-300%
Lifecycle Carbon Intensity	38g CO_2e/kWh	5g CO_2e/kWh	5g CO_2e/kWh	126g CO_2e/kWh

Table 5: A summary of the metrics presented in Chapter 2. Numbers are based on data collected in the field about existing, commercially available technologies and do not include prototypes or tests under laboratory conditions.

	Electricity	Fuel Oil	Natural Gas	Coal
Cost of energy[8]	\$0.14/kWh	\$3.02/gallon [22]	\$2.00/therm [28]	\$52.01/short ton [29]
Cost of heat	\$1.10/therm, \$4.11/therm[9]	\$3.90/therm [28]	\$2.60/therm [28]	\$0.26/therm [29]
CO2e Emissions	Depends on fuel mix	7.397 kg/therm [21]	5.307 kg/therm [21]	9.553 kg/therm [21]
Amount of fuel used to produce 1kWh electricity	N/A	.078 gallons [30]	.0781 therm [30]	1.10 lb [30]

Table 6: Fossil fuel metrics. Costs are provided in the unit regularly used to measure amount or in therms.

The systems outlined in this chapter represent cutting edge solutions for renewable urban energy and heat generation. Though none of these technologies have been implemented on a

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[6] A therm is equal to 100,000 British Thermal Units, a measure of heat. It is also used to measure quantity of natural gas: 1 therm equals 96.7 cubic feet of natural gas.
[7] Efficiency depends on the type of panel or turbine used. Numbers provided are estimates of highest and lowest bounds.
[8] Data for November 2018.
[9] The first number is for a grid-tied ASHP, the second is for a traditional electric resistance heater.

city-wide scale or in a hybrid system outside of proof-of-concept experiments, they have been used extensively to help homesteaders produce off-grid power and to electrify microgrids for rural populations. This is reflected in the literature that informs this chapter. Solar photovoltaics, as one might expect, have been studied extensively by researchers around the world. Micro-hydropower has mainly been used and studied in the field in Europe and Asia. In-pipe turbines have been theorized and tested in many countries, though scholarship centers on China and Great Britain and the major companies producing the turbines are located in Europe and the U.S. Lastly, literature surrounding air-source heat pumps, particularly in cold regions, predominately originates in China. Where possible, examples of these systems in practice in urban areas and information directly from producers and installers of these technologies have been included to give a practical sense of how these systems would work in practice in Lewiston.

All of the technologies discussed in this chapter are currently available, have been proven effective in the field, and are able to be wired into the existing electrical grid to provide power to the local population with no additional major infrastructure. The four systems outlined below have been chosen for their cost-effectiveness and suitability to the environment in Lewiston, Maine; many more types of generators exist that may be suitable for other landscapes and budgets. Additionally, though microgrids, batteries and other electricity distribution and storage methods are of critical importance to the transition to sustainable energy, they are outside the scope of this chapter and will be addressed in Chapter 4. This chapter will introduce each type of energy or heat generation system with a short explanation of the technology itself, followed by an analysis of its sustainability and costs as well as potential shortcomings and its suitability to an urban landscape in Maine.

Chapter 2.1: Solar Photovoltaics

Originally developed as a rugged and constant fuel source for spacecraft, photovoltaic (PV) panels are efficient, scalable, and require no moving parts and therefore little maintenance [31]. PV panels turn sunlight in the form of photons into useable electricity in the form of a direct current. Then, an inverter connected to the panels then converts the direct current into alternating current that can be used by appliances, stored in a battery, or fed into the grid [32]. The simplicity of their setup allows PV systems to be adaptable to a variety of locations and configurations. The systems are extremely scalable; they can be small enough to fit in a backpack or large enough to provide hundreds of megawatts of electricity. This allows arrays to be fitted perfectly to the needs and resources of the user. This section will focus on building-scale, grid-tied PV systems, the smallest of which provide enough power to sustain one building's internal needs, which are often placed either on the roof of the building or in rows of angled panels in a field, on a parking structure, or other nearby open space.

Because they run on sunlight, solar panels only produce energy while the sun is up. On cloudy days, their generation is less than the maximum production by an unpredictable amount. A solar array well-suited to the building it powers will produce enough energy while the sun is up (on a day with average temperature and weather for the area) to cover the building's electricity needs for the entire day (see Figure 5). In a grid-tied system, the grid acts as a sort of battery, accepting the excess solar generated during the day – making the daytime grid fuel mix more sustainable – and then providing electricity from other sources to the building at night. Even though the building isn't technically providing all of its own power, it is offsetting its electricity use by producing enough to cover all of its needs. In residential applications, peak production coincides with periods of lower consumption as occupants are at school or work and most lights are off. The consumption curve looks different for different types of commercial buildings, but in most cases, it will be somewhat flipped from the residential curve as people come to work during the day and leave at night.

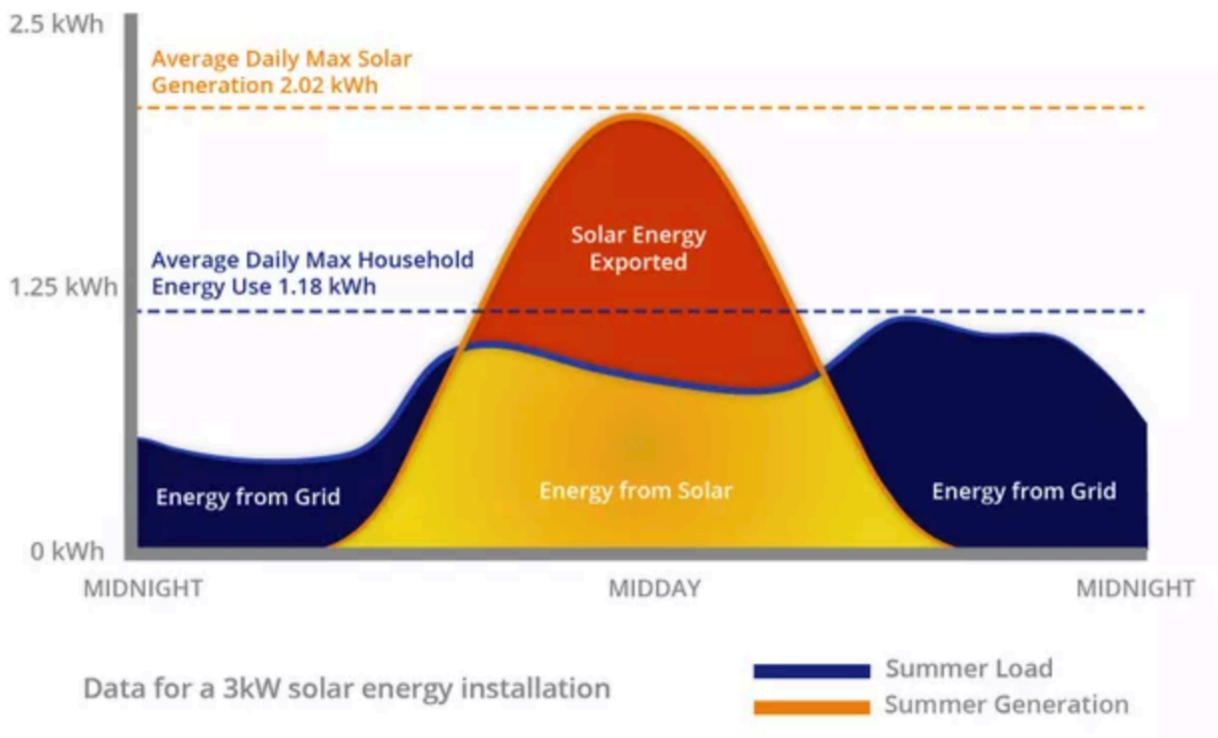

Figure 5: An example of average daily household energy consumption and solar power generation [33].

The PV panels themselves are made of either a semiconductor (in silicon, multijunction, or thin-film solar panels) or carbon-rich polymers (in organic PV panels) protected by a sheet of hardened glass or other transparent material [34]. Currently, silicon panels are the cheapest, most accessible, most durable, and most efficient type of panel, though both thin-film and organic PV promise reductions in cost and increases in the types of surfaces used to generate solar power. However, current prototypes of these panels provide slightly less efficiency and have a shorter lifespan than silicon panels [34]. Multijunction solar panels, which are made of multiple layers of different types of semiconductors, are consistently substantially more efficient than other types of panels under lab conditions but are much more expensive to create and are therefore not used in commercial solar arrays [35].

The materials used to make the panel, and the chemical and electrical interactions they facilitate, affect the panel's efficiency. Each photovoltaic material used to make a panel is only able to convert certain wavelengths of photons into electricity; this creates an inherent inefficiency within the panels because sunlight is comprised of photons with a wide variety of wavelengths. Put another way, the nature of the PV material inhibits the amount of energy that can be captured. This inefficiency can be decreased by combining more types of PV materials into each panel, creating a multijunction panel [35]. In laboratory conditions, a prototype multijunction panel captured and converted 46% of the available energy into electricity [36]. Silicon panels, which are made of only one PV material, have been able to achieve 27.6% efficiency under lab conditions [36]. The maximum efficiency of a PV panel is bounded by the Shockley-Quessier limit, which predicts the maximum efficiency of the materials it is made of [37]. For silicon panels, this limit is 33%: current silicon panel prototypes are performing near maximum efficiency. This represents a considerable increase since 2010 when the best panels were performing at 14% efficiency [38]. In the field, however, panels are less efficient than under laboratory conditions. The top 30 commercial silicon solar panel producers' average inherent panel efficiency is 16.8%, though the Sunpower X-series, the most efficient commercially available panel, achieves 22.8% efficiency and several other companies are breaking 20% [39, 40]. In practice, energy is lost through the reflectivity of the panels, environmental factors like dust, snow, and clouds, and physical factors like imperfect siting and installation, so actual electricity production is slightly lower than what would be predicted by the panel efficiencies.

Though not every day is optimal for electricity production due to environmental factors, PV panels continue to produce energy under a variety of conditions. In the Northern hemisphere, panels generate maximum energy throughout the year when sited facing due South and at an angle equal to their latitude, though they still produce energy at a wide range of orientations [41]. In Maine, panels oriented between 43 and 62 degrees will receive between 4 and 5 kWh/m^2/day of solar radiation (see Figure 6) [42]. In New England, regular precipitation ensures that panels that are properly angled and installed will self-clear of dust, pollen, and fallen leaves, and solar radiation combined with the angle of the panels clears off fallen snow [43]. Accounting for these inefficiencies, Revision Energy, a large PV system installer in Maine, reports that reliably producing 1kW of energy in Maine requires 6 m^2 of panels [43].

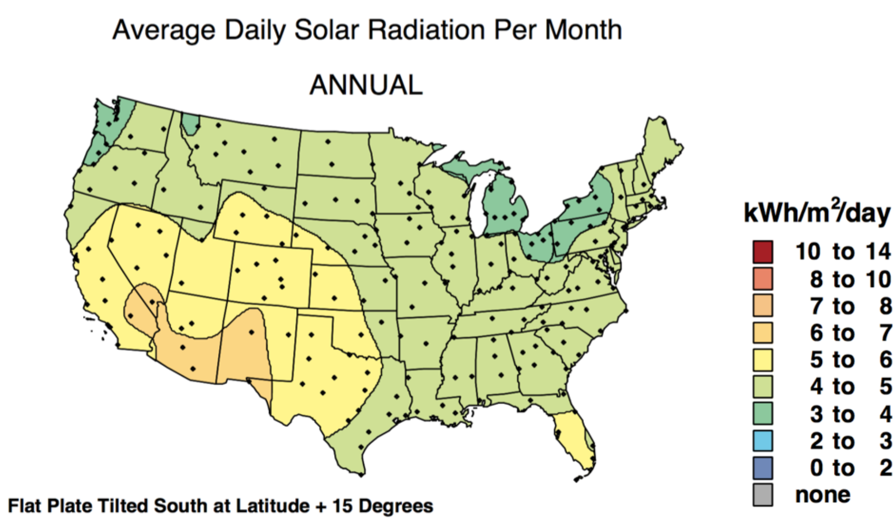

Figure 6: Average Daily Solar Radiation in the contiguous US received by a panel facing due South at an angle of the latitude plus 15 degrees. Figure adapted from NREL [42].

Despite having below average solar resources due to its latitude and climate, Maine has some of the greatest potential for rooftop PV generation in the entire country (see Figure 7) [44]. The state has a high percentage of rooftops suitable for PV installation and a lower than average electricity consumption, which combine to create an opportunity to generate 60% of the state's power – up to 6.3 GW – through rooftop solar [44]. This number is conservative; the data only includes existing rooftops, not other spaces that can be used or converted to hold solar panels such as vacant lots, parking structure covers, and the sides of buildings. The calculations are also based on a 16% panel efficiency, though if all panels were 22.8% efficient, as will be the case in the near future, Maine could produce 85.5% of its power just through PV on rooftops. Even with the panels currently on the market, places in the US with below average solar resources, like Maine, stand to produce large amounts of their energy from solar alone – and future advancements will continue to increase the amount of power generated.

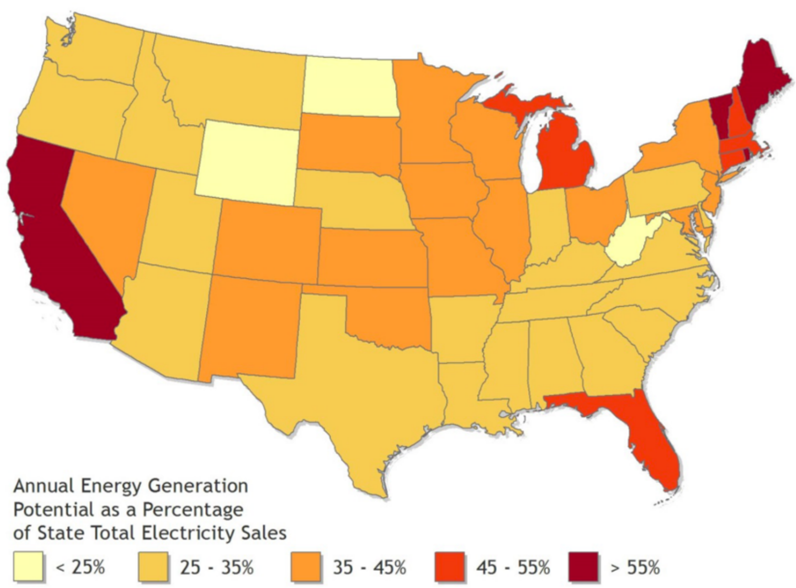

Figure 7: Potential annual generation from rooftop PV on all buildings as a percentage of each state's 2013 total electricity sales. Figure from NREL [44].

The cost of PV panels has been decreasing at the same time that efficiency has been increasing. Since 2010, the average cost of a silicon photovoltaic panel has decreased by 60% [44]. There has also been a marked increase in accessibility over the last decade due to economies of scale and technological advances that are likely to continue into the future [31, 45]. In many countries including the U.S., the price per kilowatt hour of solar power is comparable if not better than the price of power produced by fossil fuels [31]. The increasing efficiency of the panels will further reduce the price of electricity, creating natural incentives for solar installation [31]. Because PV panels produce electricity for free, all of the cost is tied up in installation and maintenance. Revision Energy's average residential PV installation in 2018, which included 25 panels, cost $28,000 before state and federal incentives [43]. These panels produce 6.25 kW of energy – enough to comfortably power the average home and sell some energy back to the grid –for a projected lifetime of 40 years. They will occasionally occur maintenance costs, though those are generally infrequent because of the simplicity and durability of PV systems. Over a very conservative 25 year lifetime of panels installed today, the LCOE from solar will be $0.09 per kWh [28]. For comparison, Maine's average cost of electricity in 2018 was $0.14 per kWh. To make installation more affordable, many solar energy companies offer financing plans that result in zero upfront cost and a locked-in price for electricity, usually less than or equal to the price of grid electricity, for a fixed amount of time until the owner has paid off the panels or reached the end of the lease.

Both buying the panels outright and leasing offer financial incentives in the form of a reduced electricity bill. The arrays offer many benefits for the building owner beyond the purely financial; they provide resilience to power outages, insulation from grid electricity price hikes, social capital from being sustainable, and a reduction in the household's greenhouse gas production. Usually, rooftop photovoltaic installations happen when the building owner independently decides to install panels through a private company because they were moved by some combination of these incentives. This practice has worked well enough in suburban and rural areas in regions with favorable regulations but does not work as well in cities where roof space is predominantly provided by apartment buildings and businesses and where buildings are rented and house multiple companies or households [7]. In these situations, tenants are not able to install PV on their buildings and incentives (particularly social and environmental ones) are less powerful to off-site building owners, which reduces rates of installation [7]. In cities, innovative financing systems are needed to ensure that solar is accessible and incentivized on all suitable buildings. Some megacities like New York City are pioneering multitenant and industrial solar financing systems, but the technique has yet to reach smaller cities like Lewiston. This is discussed further in Chapter 4.2.

Economic or governmental incentives for solar PV installation are critical to building hybrid distributed renewable energy networks and transitioning the world away from fossil fuels. Considering the density of flat, unused space found on urban rooftops and the falling price of PV panels, solar power is an important component of any city's renewable energy portfolio. Cities of all sizes are adopting policies that encourage the adoption of PV panels on city-owned buildings and single family homes with massive success [46]. At the end of 2017, just 20 U.S. cities provided over 2 GW of PV capacity – more than the entire United States had installed at the end of 2010 – proving that PV in cities is not only viable but extremely attractive [47]. In a case like Lewiston, with below-average consumption and lots of rooftop space for panels, solar will be an indispensable part of the city's renewable energy transition.

Chapter 2.2: Micro Hydropower

Hydropower is the world's oldest and largest-generating renewable energy resource, supplying 19% of global electricity [48]. However, the large dams and associated reservoirs traditionally used to harness the power of water have a variety of drawbacks: they are incredibly capital-intensive, create massive changes in the local ecosystem, require the removal of people and animals from the flooded area, and release large amounts of methane created by the decomposition of flooded flora [49-51]. Microhydropower, or MHP, systems provide the generating benefits of hydropower but have fewer drawbacks. MHP systems generate between 1 and 3000 kW of power, enough for a single system to power a house up to a small town, and are usually run-of-river, meaning that they don't trap any water behind a dam [52]. This construction minimizes the impact on the environment and surrounding community and eliminates the risk of dam failures while still providing constant power. All types of hydropower have much less variability in electrical output than solar or wind power. Additionally, MHP systems have capacity factors, ratios of actual power produced on average to the maximum power that could be produced under optimal conditions, that are greater than 50%. This is much larger than those of wind, which is around 30%, or solar, which is around 10% [51]. Put another way, the amount of power produced by MHP systems is much less variable and much more efficient than that of solar or wind; as long as there is liquid water in the stream above the minimum operating discharge[10] of the turbine, electricity is produced.

MHP systems make electricity by diverting part of a moving body of water through a pipe or channel to some kind of turbine. The energy of the water moving downhill causes the turbine to spin, then an alternator transforms the rotational energy of the spinning turbine into AC electrical energy, which can then be used. A regulator controls the entire system and shuts down the turbine in the event of a problem [53]. Available discharge also determines what type of turbine can be used. MHP systems can be installed in small streams with a head[11] of over 1 meter. Different types of turbines have different efficiencies; in general, properly sited and installed MHP systems achieve between 70 and 90% efficiency [51].

[10] The amount of water flowing through a given cross-sectional area.
[11] The upstream pressure of the water, which is related to the difference in height between the point just before the turbine setup and the bottom part of the turbine.

Turbines fall into two broad categories: impulse and reaction. Impulse turbines have a wheel suspended in the air and use the impulse force created by a jet of water deflecting off of the wheel to turn the turbine [54]. Because they require high water velocities, they are best suited for high heads and lower discharges, though studies have successfully adapted them to low heads [52]. Reaction turbines are best suited to low heads and high discharges. This category of turbine uses a submerged screw or propeller to harness the pressure created by water passing by it, following the same principles as an airplane engine. Guide vanes or a snail shell-shaped casing swirl the water before it enters the turbine, increasing efficiency [54]. Several types of turbines exist within each category, each suited to a different combination of head and discharge (see Table 7 and Figure 8).

	Head >50m	10-15m	<10m head
Impulse	Turgo, Pelton	Crossflow, Turgo, Pelton	Crossflow
Reaction		Francis, Kaplan	Kaplan, Archimedes

Table 7: Types of turbines classified by optimal head height and turbine category. Adapted from Elbatran et al. [52]

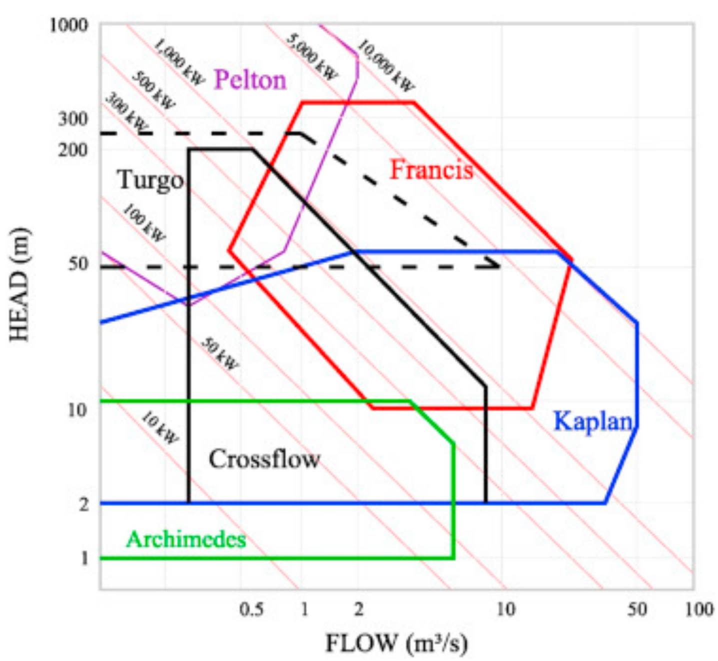

Figure 8: Types of turbines suited to different situations and their expected generation (used with permission) [52].

Relevant turbine types for MHP deployment in Lewiston include the crossflow impulse turbine and the Kaplan and Archimedes reaction turbines [52]. Pumps can also be operated as turbines (a technique called PAT, or pump-as-turbine) in these conditions by installing them backward, though each one has to be tested for efficiency and predicted power output because pump manufacturers do not provide this information [52]. PATs are generally cheaper and can be bought off the shelf for fast installation, though other types of turbines can be better adapted to the specific circumstances at the site.

Crossflow turbines operate by shooting a jet of water at a closed drum with slats on the sides: the water enters through a slat and exits through another, passing through the center of the drum and imparting its momentum to the drum on both entry and exit. The water, left with little residual energy, falls below the drum and exits through a channel (see Figure 9) [54].

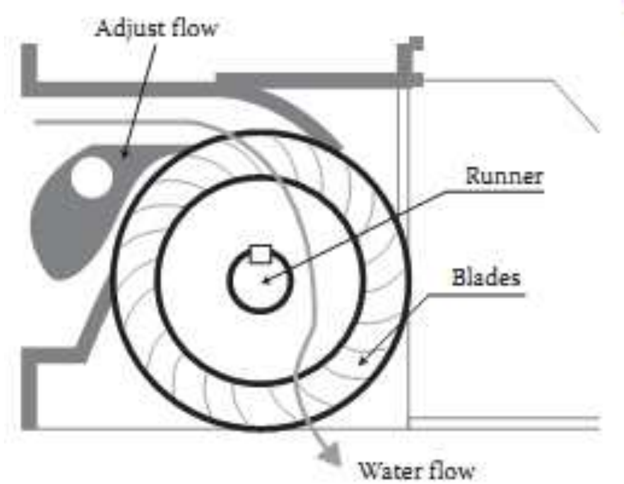

Figure 9: Schematic of a crossflow turbine. (used with permission) [55].

Kaplan turbines, which comprise the majority of installed reaction turbines, function like the propeller of a ship encased in a pipe. Water enters a spiral-shaped entry and encounters the blades of the turbine, which are pushed by the pressure and kinetic energy of the water, causing them to spin. Water then leaves through a discharge pipe (see Figure 10). The whole system is closed and filled with water to preserve pressure and provide up to 90% efficiency [54].

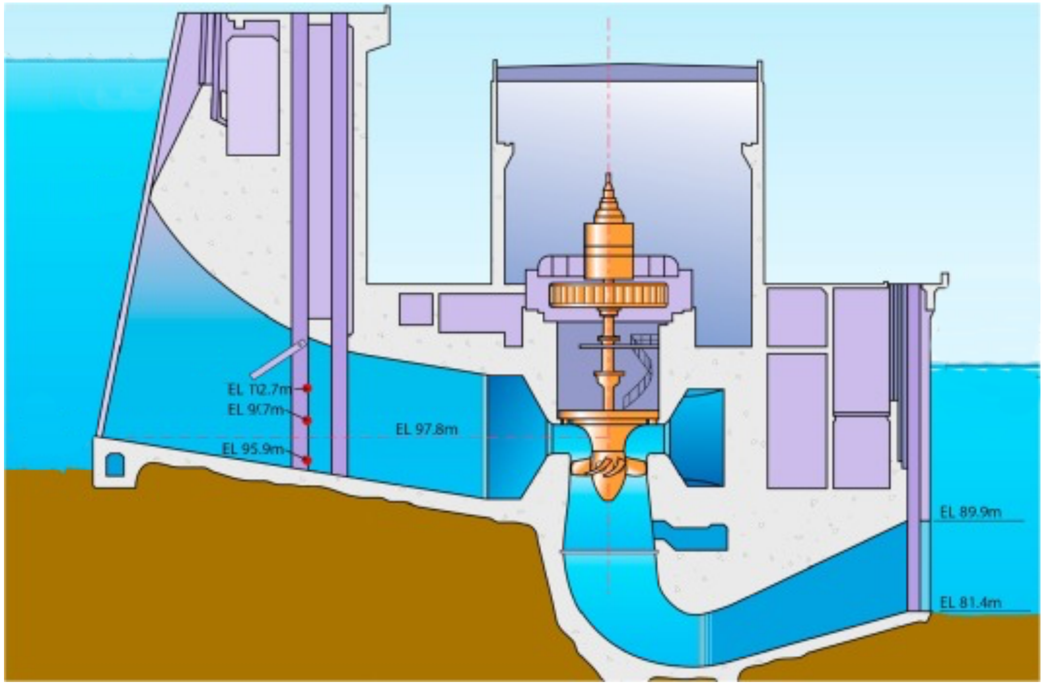

Figure 10: Schematic of a Kaplan turbine (used with permission) [56].

Archimedes turbines, which are specifically suited to large discharges and small heads, function as a giant, angled screw: water enters at the top of the screw and gravity pulls it down through the threads, spinning the turbine. Water is then immediately discharged into the stream (see Figure 11). The maximum efficiency for an Archimedes turbine is 86% [52].

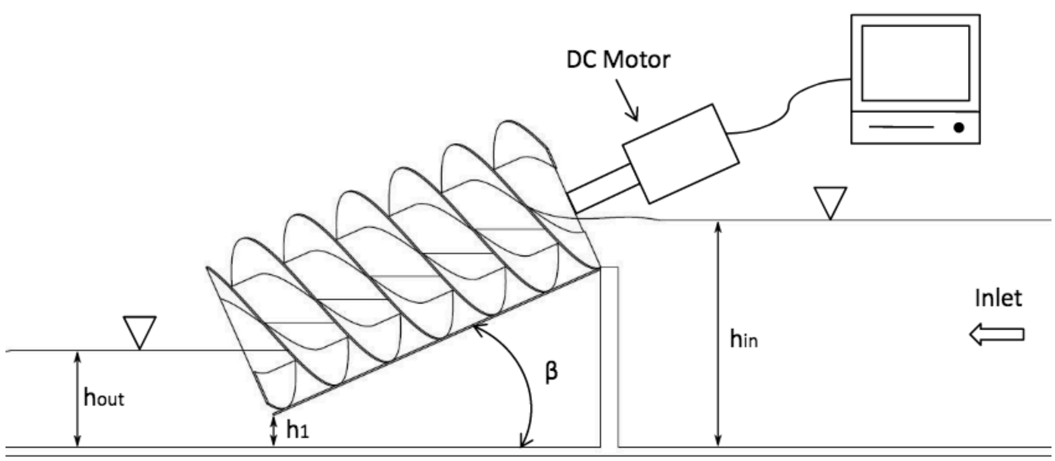

Figure 11: Schematic of an Archimedes turbine (used with permission) [57].

Though they are slightly less efficient, Archimedes turbines offer a major benefit: they are the only turbine that has not been found to damage the environment [52]. Both crossflow and Kaplan turbines require debris-free water to function, which can be achieved by placing screens of varying mesh sizes in the intake area. These screens require regular cleaning and disrupt the ecosystem by changing how objects are carried downstream. Archimedes turbines, however, only need to filter out very large debris like logs. Fish, leaves, sticks, and other objects can pass through without injury or disrupting the turbine. An Archimedes turbine is in use in the city of Freiburg, Germany with great success; it has not disrupted the stream, which has been extensively studied for rehabilitation purposes, and it produces electricity in an urban setting that powers tens of homes.

There is a large opportunity for MHP in the US; MHP could potentially provide more than 30,000 MW (30,000,000 kW) of capacity, enough to power 24 million homes [26, 58]. Though only places with relatively steep valleys and large rivers are suitable for large hydropower, MHP is suitable to a much wider variety of settings. Forty-one states have been found to have the potential to increase their hydropower generation by more than 50% through the use of MHP [58]. Though no studies have quantified the MHP generation potential in cities, the opportunity is significant because most cities are sited near or on rivers that may be conducive to MHP development.

Due to their constancy, simplicity, and durability, MHP systems are favored by homesteaders and off-grid developments. The systems can be installed by companies or bought in do-it-yourself kits and can either be installed as a stand-alone source of power or connected to the grid [53]. In an urban context, several MHP turbines could be used in succession to provide power to the grid. MHP systems have a high capital cost and low running costs, though it is hard to generalize the costs of systems because they are highly adapted to each individual site. The final cost has been found to rely on the head and discharge of the river and the generation capacity of the system [59]. That being said, MHP projects generally cost $15,000 to $25,000 per kilowatt of generating capacity and the cost per kilowatt decreases as head and/or generation capacity increase [52]. Efforts to find an equation that relates head height, turbine generation capacity, and cost have met with relative success; one used data from European MHP plants to create cost curves that fit the data for Kaplan, Francis, and Pelton turbines better than any past effort [60]. These curves suggest that turbines with heads under 100 feet and generation capacities under 250 MW should cost between $100,000 and $250,000, depending on the specific head, capacity, and type of turbine [60]. This cost can be split between the WSS, energy company, and private investors in a power-purchase agreement much like the ones available for rooftop solar installations [61]. The International Renewable Energy Agency has found the LCOE of microhydro to be between $0.02 and $0.27, depending on the type of turbine and the circumstances of the installation [62]. Standardization, increased reliance on local knowledge of river systems, and improvements in technology have brought the initial cost down and will continue to do so. The high capital cost of MHP is generally paid off over 10 or 20 years, after which power is produced for only the cost of maintenance and operation over the rest of the system's lifetime, which could be well over 100 years [54]. This makes MHP a smart investment for cities and regional governments in particular because they are generally less concerned with short-term profits and more in long-term benefits than an energy corporation.

The constant generation, widespread potential, low environmental impact, high efficiency, and low long-term costs of MHP make it an important renewable electricity generation method. The adaptability of MHP, which can fit any location and electrical demand,

and riverside location of many cities and towns make it particularly useful for urban electricity generation. Lewiston's canals are perfect for MHP development, and their regular discharge ensures that properly sized turbines will continuously operate near peak performance.

Chapter 2.3: Conduit Hydropower

Conduit hydropower, also called in-pipe hydropower, is a renewable energy technology that is exclusively useful in urban settings: it generates electricity from constant excess pressure in municipal water supply systems (WSS). WSS' are a network of storage tanks and pipes for both clean and wastewater. Most WSS' use pumping to distribute water, but pressure varies over the course of the network of pipes due to changes in topography and pipe diameter [63]. Excess pressure can cause water main leaks and accelerate pipe deterioration [64]. Traditionally, the pressure is dissipated through the use of mechanical pressure reducing valves (PRVs) or break pressure tanks (BPTs) [64]. Reducing pressure at these high-pressure points protects the integrity of pipes, reduces the opportunity for building damage due to cavitation caused by water losses, and maintains or even improves the quality of water distributed [63, 65]. Turbines can be installed at these same high-pressure points to relieve pressure by removing energy from the system. As an added benefit, they turn it into useful electricity while providing the same services as conventional pressure-reducing techniques [66].

Kaplan, PAT, Pelton, and Francis turbines, some of the same types of turbines used for MHP, can be used to reclaim energy in pipes. The Kaplan is most suitable due to its ability to generate power from water with relatively low pressure. Additionally, two companies are also producing unique turbines for use specifically inside water distribution pipes: Lucid, in Portland, Oregon, and Zeropex, in Berkshire, UK. The Lucid turbine is spherical with airfoil blades that spin when water passes through it (see Figure 12). Lucid is a brand name for a spherical turbine, which can have 5 or 8 blades and can generate electricity from water without sapping much of the water's kinetic energy [67]. Because of this, spherical turbines are good for use in the large gravity-fed pipes that bring water into a city but cannot be used as a PRV replacement like the other types of turbines. The Lucid turbine is designed to be used in larger 24"-60" water distribution pipes. The standard configuration, composed of 4 Lucid turbines in line in one pipe, can produce 24kW of electricity in a 24" pipe and 100kW in a 60" pipe [68]. The Difgen turbine from Xeropex, on the other hand, is designed specifically to replace PRVs. The Difgen produces 11 to 30 kW and actually provides better control over water network pressure than a PRV [69]. Unfortunately, more information about how it works is not yet available to the public.

Figure 12: Schematic of a Lucid turbine [68].

PRVs, or PRV replacements, are necessary because points along the water distribution network develop constant areas of higher or lower pressure due to changes in topography and pipe diameter. Because the WSS is a network, action to dissipate excess pressure has to take into consideration the downstream effects on areas of low pressure and ensure that all customers are delivered water at at least the minimum pressure required by regulators [63]. Therefore, the pressure that needs to be dissipated, and energy that can be generated, depends on the individual point of high pressure in the network. This variability makes the potential for generation difficult to generalize; electricity output can only be quantified through individual case studies. A study compiling data from past installations and models found that a single turbine will produce up to 47 kW, a generation capacity that is borne out in other studies and in practice [70]. Case studies done in Fribourg, Switzerland have determined that 9 turbines installed to replace PRVs in the city would have 49 kW of capacity and produce 429.5 MWh per year [71]. An existing series of conduit turbines in Pompeii have capacities between 2 and 11kW [66], an experimental eight-bladed spherical turbine is generating 700 MWh per year, in Hong Kong [67], a turbine replacing a BPT in Kildare, Ireland is producing 27 kW capacity, or 237 MWh per year [72], and a four-turbine system is providing 200kW capacity inside a 42" pipe in Portland, Oregon, enough to power 100 average American homes [68]. Generation capacities vary based on turbine type, the layout of the WSS, and the topography of the city.

There is other potential for generation inside WSS' beyond installation in water distribution pipes: turbines can also be installed at places where lowering water pressure would not be detrimental to customers, such as at the outlets of storage tanks and inlets and outlets of wastewater treatment plants. CHP at wastewater treatment plants has been found to provide up to 200 kW of generating capacity [65]. However, CHP in wastewater treatment plants presents different challenges than those installed in drinking water as debris needs to be screened out and more robust turbines need to be installed. The extra cost associated with wastewater-proofing a

CHP system is compensated for by the energy generated. Combined, the potential generation of conduit hydropower at PRVs, BPTs, and wastewater treatment plants is large; a study of 187 potential generation sites in Wales was found to be able to provide 10.82 GWh/year, which corresponds to a savings of €1,298,000 per year ($1,295,000 per year in 2018 US dollars) on energy costs [65].

All of the variables described above make the cost of a conduit installation hard to estimate. Adapted MHP turbines themselves should cost about the same as they would in an MHP setting, though installation cost would be much higher due to the amount of construction work involved in fitting a turbine into an underground system. Neither Lucid or Zeropex provide prices for their turbines on their websites because the cost involved with each case varies so greatly. A Lucid turbine installation in Portland, Oregon cost $1.7 million including labor, construction, and permits [61]. The cost was shared by the WSS and a private investor. Numerous studies have estimated that the payoff time for the installation of one of these systems is between 10 and 20 years and the LCOE is between 5 and 12 cents per kWh, making conduit hydropower in water delivery pipes an effective investment for a city government [60].

Conduit turbines are a natural choice for urban energy generation given that they are specifically suited to urban environments. Their LCOE and generation potential makes them even more suitable to smaller cities such as Lewiston. Though their upfront cost is high compared to the other renewable energy technologies in this study, it is very low compared to traditional large hydropower dams. Additionally, all of the electricity is generated invisibly; in-pipe turbines take up no usable space, are installed in places along the WSS that are not seen by the public, and, as long as turbines are correctly installed, cause no change in water pressure or quality [73]. This removes any potential barriers created by public backlash to large renewable installations. Additionally, conduit turbines are ideal for cities with aging infrastructure as they require no additional work to install when new pipes are being laid. Based on this information, CHP is ideal for Lewiston.

Chapter 2.4: Air-source Heat Pumps

Air-source heat pumps (ASHP) are unique amongst the technologies included in this paper because they do not produce electricity; they use it to move heat from the outdoors to building interiors. This is important because most space and water heating in Maine is achieved through the onsite burning of fossil fuels, creating an entirely separate source of emissions from electricity production. Currently, two-thirds of the average U.S. household's energy use goes exclusively to space and water heating [74]. ASHP can avoid the emissions and cost associated with fossil fuels by providing space heating and air conditioning – which is increasing in popularity in Maine as summers get hotter – in one electrically-powered unit [75, 76]. Of course, the carbon emissions of a grid-tied ASHP system depend on the fuel mix of the local grid. In any case, electric heating provides a massive decrease in emissions compared to Maine's preferred fuel oil. ASHP shifts the burden of emissions from the building owner to the electric utility; the fuel that heats the home is no longer oil burning in the furnace of each building, but electricity produced mainly by commercial generators, which are getting less carbon-intensive every year. This shift can also alleviate local air pollution issues, which are magnified in urban environments by the density of buildings burning oil, because no exhaust is being released near the building being heated [77]. In a local renewable energy regime like the one proposed in this paper, the environmental benefits are even more pronounced. With a cleaner grid or when combined with the other renewable electricity production techniques discussed in previous sections, ASHP provides a sustainable solution for heating and cooling.

ASHP systems operate on the same principle that powers refrigerators; they use electricity to transfer heat from one place to another. Configurations of coils and heat dispersal methods vary, but in general terms the heat is carried through two connected coils of copper tubing, one inside and one outside of the building, that contain refrigerant that flows between the coils in a loop. In heating mode, a fan inside the outdoor unit blows air over the coil, which allows the refrigerant to collect low-grade heat from the air. The heated refrigerant then concentrates the heat and evaporates into a gas that travels to the second coil inside the building. There, another fan blows air over the coil, transferring the high-grade heat to the indoor air and moving that heated air through ducts or another dispersal method to heat the building [77]. The refrigerant then cools and condenses into a liquid that travels back outside and the process repeats. In cooling mode, a valve reverses the flow and heat is transferred through the same method from inside the building to the exterior [78]. In a ductless ASHP setup, the coils and fans are housed inside two units: an outdoor unit that is comparable in size to a conventional air conditioner and an indoor unit that is comparable to a wall mounted electric heater. Heaters are sized from 6,000 BTUs per hour, which heats around 400 square feet of building space, to 18,000 BTUs per hour, which heats 1,200 square feet [79]. ASHP is most suitable to well-insulated apartments and homes with open-concept layouts where air can circulate around a large space [79]. Additional tubing and indoor units or ducts can be installed to heat different rooms, though this adds cost. For larger homes, more than one heat pump can be installed, but this is less energy efficient than having one larger heat pump. Rooms that are more closed off or colder can be heated with separate electric resistance heaters, which use 2.5 times more energy than ASHP but are more versatile in terms of applicability to spaces.

Installation of ASHP systems is relatively easy and many firms around the region specialize in air-source heat pumps. Ductless units can be installed in existing homes without much retrofitting. Ducted and short-run ducted systems can be installed with a more serious retrofit or as a new building is being constructed to provide heating throughout the house more efficiently. In existing buildings, all types of ASHPs can be used as a primary heat source while keeping the existing fossil fuel or wood-powered backup for rapid heating and supplementary heat on the coldest days, so the building owner does not have to remove the existing heating infrastructure [80]. This backup is generally not necessary in full retrofits and new buildings. Cold-resistant ASHP systems, which include defrosting capabilities, different refrigerants, and special configurations, can provide adequate space heating at temperatures as low as -30 Celsius, which is more than enough cold tolerance for Maine winters [75, 77]. ASHP systems provide constant, low-intensity heat, meaning that they are not suitable for drafty rooms, buildings with ceilings higher than 10 feet, warehouses, and other large, cold spaces. They also cannot change a room's temperature quickly, so they are best suited to buildings that are constantly occupied like shops and homes [79]. Electric resistance heaters can be installed to heat spaces more quickly.

Technologically similar systems can be used to collect heat from the Earth or bodies of water, though these are much more expensive and require a much more intensive installation process. Due to these concerns, they are not particularly relevant in urban areas, though they may be useful in other contexts or if they are installed when new buildings are being constructed. New configurations of ASHP systems are also becoming more common. The most promising type can be set up to heat water alone or water as well as air; though this technique is popular in Europe, many American systems are currently in the permitting process and should become more available in the near future [79]. For water heating with ASHP, the indoor coil passes through an insulated water tank. The heated water can then be used for underfloor heating, traditional baseboard or radiator heating, or just for hot water. These air-to-water heat pumps can work with existing heating infrastructure in homes with even less installation required than a ductless air source heat pump, making them ideal for retrofitting older homes.

ASHP of any kind provides reliable heating at a significantly lower cost than any other heating method [77]. These systems, which move heat instead of creating it, have a coefficient of performance between 2 and 3, meaning that they use 2 to 3 times less energy than a traditional electric space heater to heat the same space [28]. Economic analyses have shown that ASHP systems are the cheapest way to heat space when compared to all other traditional heating methods [77]. In Maine, the average ductless ASHP system costs $5000 per indoor unit, including installation [79]. Though the initial investment in an ASHP system is higher than that of a gas heater, electric heater, regional steam heating, or cogeneration, the running and maintenance costs are lower than those of any other heating method [77]. To lessen the upfront investment required to transition to electric heating, Efficiency Maine, a state energy efficiency organization, offers a rebate for residential electric heating installation: $500 off the first indoor ASHP unit and $250 off the second [80]. For commercial customers, the rebate ranges from $500 to $1,250, depending on the size of the space and the number of pumps needed.

Considering that ASHP can also heat water and provide cool air, thereby replacing the furnace, hot water heater, air conditioner, and all of the fuel or electricity needed to run them, this system is even more economically advantageous. The savings from a grid-connected ASHP system take between 4 and 7 years to pay back the initial investment [77]. ASHP systems can be optionally tied to rooftop solar arrays, which provides free energy to power the system and creates a shorter payback period. Revision Energy, the largest installer of ASHP systems in Maine, has found that the average heat pump in the average Maine house uses 2,500 to 3,500 kWh of electricity per year, costing $350 to $500 per year at current grid electricity prices. Revision estimates that the grid electricity required to heat the average home that they work on for one year would cost $1,706, and an electric heating system powered by rooftop solar[12] would heat that same home for $1,023 [28]. For comparison, heating oil for the same house would cost $3,120. Revision's estimate is significantly more than the estimate of the average Lewiston house's heating oil use; this is due to the fact that Revision mostly works on medium-to-large houses and Lewiston's housing stock is primarily apartments. The figures are also impacted by the fact that heating oil prices are extremely volatile; the average cost of oil in 2017, which is used Lewiston's baseline calculations, was $2.66 per gallon. The price in October 2018, which is used in the Revision estimate, was $3.02 per gallon [22]. Electric heating does not face these price swings, making it a better option for lower income families.

The cost, efficiency, and weather resistance of ASHP systems make them ideally suited to heating Maine's buildings. The fact that they produce no exhaust and have no fuel to spill or cause a fire makes them excellent for application in urban settings. Additionally, the urban heat island effect, which keeps urban areas at a warmer temperature than surrounding areas, makes ASHP systems even more efficient as they have comparatively more heat to collect than a similar building in a rural area. Their short payback period and low operating costs makes ASHP a good heating alternative for economically burdened communities. Even though they do not produce electricity, ASHP systems are an essential component of the urban transition to renewable energy.

12 At an LCOE of $.09/kWh [28].

Chapter 3: Implementing Distributed Hybrid Renewable Energy in Lewiston

This chapter models the implementation of a distributed hybrid renewable energy system, composed of the generators described above, in Lewiston. The model estimates what the resulting system would create in terms of electrical generation, greenhouse gas emissions, and economic profit. Electrical generation is compared against Lewiston's current residential and commercial electrical use as calculated in Chapter 1. Heating potential is calculated for and compared against only residential heating fuel use due to constraints on available data. All calculations are estimates based on the best available data and errors are noted where appropriate. Basic methodology is included in the chapter. A more detailed methodology can be found in Appendix C.

Chapter 3.1: Creating a Solar City

Lewiston has great potential for solar energy. As mentioned in the previous chapter, central Maine isn't the most ideal location for PV in the country, in terms of solar resources. However, Lewiston does have two things going for it that make rooftop solar an attractive technology: the city has a lot of roof space, and roofs here are built to handle snow so no additional work needs to be done to ensure that they are strong enough to hold solar panels. In addition to private homes, large riverside mill complexes and industrial buildings provide much of the city's rooftop area. The available space means that Lewiston can adopt solar without substantially changing the layout or aesthetics of the city, as would be necessary with the introduction of ground-mounted, industrial-sized solar arrays.

The calculations in this chapter are based on data from Project Sunroof. The Google-backed project uses Google Maps satellite data and machine learning to estimate the amount of electricity that a given area could produce if every viable rooftop surface was covered with solar panels. The machine learning algorithm identifies and measures roofs, accounting for shading, seasonal variability, local weather patterns, and roof pitch and direction, then estimates the electricity that could be produced by the rooftop. This creates a relatively accurate portrait of generation potential over an area [81].

The arrays suggested by the model have some parameters that mirror how they would be installed in real life: the model only includes roofs that can support between 2kW and 1MW arrays, so small spaces like shed roofs are not included. Individual arrays must be composed of more than 4 consecutive panels to be considered, and every panel has to receive at least 75% of the maximum solar energy available in the county the array is located in – this eliminates panels that are too shaded or at too much of an angle to make sense in a real installation. However, there is potential for error in the algorithm; because it uses Google Maps data, the algorithm may miss roofs or include objects that are not roofs if they are not correctly identified in Google Maps [82]. Additionally, though larger features like chimneys are accounted for, small features on roofs like vents and satellite dishes are not included even though they reduce the area available for panels. The model also works with satellite images that are taken periodically. The calculations in this chapter are based on a Project Sunroof dataset from May 2018, and there may have been construction or demolition in the city since then, adding a small amount of error to the total roof area [81]. The rooftops identified in Lewiston, for the most part, seem to be accurate, though there may be small inaccuracies in the calculation of roof area, angle, or direction.

These errors, which inflate the total potential generation, are far outweighed by the errors that underestimate it. Most noticeably, a piece of the southern part of the city is listed as having no viable roofs even though there are buildings there, so the potential area within city limits available for solar generation is larger than that given by the algorithm. Additionally, parking lots, though Lewiston has many of them, are not included in the model, even though they are prime real estate for solar arrays. 23% of the area of downtown Lewiston is dedicated to parking – an incredible amount of space that can be easily converted into dual parking-power production space through the addition of a roof structure [5]. Because these parking areas are not included in this algorithm, the following calculations substantially underestimate the total solar potential within city limits. Lastly, comparisons with existing arrays show that the model tends to underestimate solar potential on individual rooftops as well as on the city-wide scale. For example, a house in Auburn, Maine, Lewiston's sister city on the other side of the Androscoggin River, is rated by Project Sunroof as being able to support 3kW of panels [81]. However, a Revision Energy analysis completed in 2017 found that the house could actually hold an 11.7kW array consisting of 30 Q-Cell panels [83]. The completed array provides all of the electricity used by the building, including the demand created by an air source heat pump and an air source water heater which were both installed with the solar array. Clearly, there is more potential in Lewiston than the algorithm suggests. With these errors accounted for, the net underestimation of potential is preferable to overestimation due to the fact that, in practice, the city will probably never obtain 100% coverage of all available roof space by solar panels. Underestimation helps provide a better picture of how the city's energy network would function in practice.

There are two significant sources of error in the algorithm that are too far from reality to accept. Firstly, the Project Sunroof algorithm assumes industry-standard efficiencies for everything but the panels and inverters; it assumes that the panels have 15.3% efficiency and the inverters 85% efficiency [82]. This is a significant divergence from industry-standard specifications; as discussed in the last chapter, average panel efficiencies are much higher than 15% and inverters commonly used in small solar installations are at least 95% efficient in converting the power produced by the panels into usable electricity. Secondly, the model assumes that panels will be flush with the roof surface, even though this is not optimal for power production at Lewiston's latitude. The calculations in this section will address these three sources of underestimation present in the algorithm – panel efficiency, inverter efficiency, and the tilt of panels on flat roofs –to provide a more accurate idea of the solar generation potential in Lewiston.

Project Sunroof's model estimates that there are 13.9 million square feet of space across 9,200 roofs viable for solar power generation within Lewiston's city limits [81]. With their model input of 250W panels with 15% panel efficiency, covering all available roof surfaces with solar panels would result in 197 MW generation capacity. Put another way, Lewiston would produce 197 MW electricity on the sunniest possible day when panels are installed on every single roof identified in the model. Keep in mind that this will hardly ever happen; most of the time, the panels will be generating below capacity, and Lewiston will probably never get to 100% panel coverage. Including seasonal variability, weather, and an 85% inverter efficiency, which is introduced when the inverter changes the panel's produced DC electricity to AC electricity that is useable by appliances, Project Sunroof estimates that Lewiston could produce 223,000 MWh of AC power per year [81].

The model can be improved by aligning the panel efficiency, inverter efficiency, and panel tilt with industry standards. This was calculated by removing the inefficiency created by the model assumptions, which leaves only the yearly solar radiation received by the roofs in the model, and then applying the inefficiencies associated with the improved scenario. Significant increases in generation capacity and total yearly generation potential arise from simply taking the panels on flat roofs and putting those panels at a 44-degree angle, the same as the city's latitude, which ensures that the panels receive the most direct sunlight throughout the year. Just tilting the panels adds an additional 30,600 MWh of potential electrical generation per year (see Table 8). By only installing Revision's preferred inverters, the Solar Edge Single Phase Inverter SE300H-US, and leaving the panels at the 15.3% efficiency and horizontal tilt assumed in the model, potential generation increases by 14% [84]. By installing Q Cells Q.Peak Duo G5 320 watt panels, the type that Revision Energy uses in standard residential arrays, and leaving all else the same, the total yearly generation is improved by 21%. The Q.Peak Duo G5 panels are affordable, operate well in Maine weather, and, most importantly, achieve 19.3% efficiency, far outperforming the model's panels [85]. Combining all of these improvements, which realistically reflect the landscape of solar installation in Maine, into one scenario improves Project Sunrise's estimate for yearly generation potential by 40%, bringing Lewiston's potential generation up to 373,000 MWh of electricity per year.

Scenario	Panel Efficiency	Inverter DC-AC Conversion Factor	Total Generation Capacity (MW DC)	Total Yearly Generation Potential (MWh AC/year)	Percent Better Than Model
Model Assumptions	0.15	0.85	198	223,000	---
Panels On Flat Roofs Are Angled	0.15	0.85	224	254,000	12%
Install More Efficient Inverters	0.15	0.99	229	260,000	14%
Install More Efficient Panels	0.19	0.85	249	281,000	21%
All Improvements	**0.19**	**0.99**	**329**	**373,000**	**40%**

Table 8: Scenarios for solar installation in Lewiston.

All of these estimates provide more than enough power for Lewiston – the city's residential and commercial buildings only use 170,000 MWh of electricity per year (see Chapter 1). The model that realistically reflects how the panels would most likely be installed provides over twice that much electricity. Further potential to increase generation exists; the scenarios presented above only consider the materials that Revision is currently using. With the best panels on the market, the Sunpower X-series, and the other improvements to the model, Lewiston could produce 440,000 MWh a year, a staggering 97% more electricity than the Project Sunroof model and 61% more than the city currently uses. Any of the above scenarios would provide enough electricity to power all of the city's residences and commercial buildings with enough left over to power industrial facilities and/or sell to the grid.

It is important to note that though the Project Sunroof yearly estimates include a rough estimate of changes in production due to seasonal variability and weather, the panels' production will likely be below the estimation. More significantly, the model assumes that every possible roof that could hold a solar array does; these estimates reflect the best-case scenario of 100% solar adoption. This, of course, comes with a cost.

National data on average residential solar array price predicts that it will cost nearly $160,000,000 to equip the majority of the 9,200 available roofs with residential size-solar. 643 arrays are not accounted for in this figure; they are outside the normal bounds for residential-sized solar arrays and will be discussed later in this section. The estimate for the majority of roofs is shown after including the current 30% federal tax credit – however, at the time of writing, this credit is set to step down to 26% in 2020, 22% in 2021, and 10% from 2022 onwards [86]. Hopefully, the tax credit will be reinstated in the future to re-incentivize solar adoption for economic and environmental reasons. Maine currently has no additional tax incentives, though this may also change with future legislators [87]. The prices below are presented as base costs and post-30% tax credit costs to make estimation of future costs easier. The number of roofs comes from the Project Sunroof model, and the cost data from Energysage, a website powered by the U.S. Department of Energy Sunshot Initiative [81, 88]. The 11.7 kW array in Auburn described above cost $24,608 before the tax credit and $17,226 after, which is in line with the Energysage estimates[13] [83].

Though implementing solar seems expensive, the panels can be financed through existing solar financing schemes that allow building owners to make a significant profit from their panels with minimal upfront investment. These residential-sized solar arrays are already financially incentivized and the addition of state or local tax credits would further encourage the fast and full adoption of solar PV on residential roofs.

The remaining 643 roofs accounted for by Project Sunroof are larger arrays (30-1000 kW) that fall in industrial array territory, allowing for cheaper prices and different financing strategies. However, corporate secrecy and the unique requirements of each large array make finding good estimates for the price of an industrial array by megawatt – including components and labor – difficult. These arrays can be financed by private companies, the electric utility, the city, building owners, or some combination of these groups to lower the financial burden on any individual entity, and many case studies exist of these types of schemes working in practice – a similar case will be discussed in the next section. Fortunately, the Q.Peak Duo solar panel used in the calculations in this chapter is rated for industrial rooftop applications, so all other estimates in this chapter are applicable to the larger arrays.

Another way to contextualize the cost of solar in Lewiston is through levelized cost of energy[14]. Solar power's LCOE is much lower than the current price of electricity and because it is produced onsite, transmission losses and fees are irrelevant. Assuming that the LCOE is

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[13] See Table 12 in Appendix A for more information.
[14] LCOE, see Chapter 2 for more information.

$0.09/kWh, as discussed in Chapter 2, producing enough solar electricity to cover Lewiston's energy use would cost $15,300,000 per year – over $8,000,000 cheaper than what the city paid for the same amount of energy in 2017[15]. Additionally, full adoption of solar with angled panels on flat roofs and Revision Energy's preferred components would produce 203,000 MWh of excess energy that could be sold back to the grid to power nearby towns. The sale of this electricity at current grid rates would earn Lewiston $18 million per year. This profit would offset the entire cost of the residential-size solar arrays in just 9 years. Considering that the price of the industrial arrays was not included in the cost estimate, but the output of those arrays is included in the estimate of total potential generation potential, it is safe to apply the industry-standard assumption that the excess energy from all of the solar panels would pay for the installation of all of the arrays in 10-20 years[16]. After that time, the city would be making a profit of $18,000,000 per year for no additional cost or effort. This electricity can also be used to convert the city's heating systems, which is discussed in the Conclusion of this paper.

Additionally, adopting solar power (or any other renewable energy source) negates the carbon emissions associated with the creation of electricity through the burning of fossil fuels, which provides physical, social, and economic benefit. This is not to say that solar energy has no carbon footprint; life-cycle analyses have found that a monocrystalline solar cell manufactured in Europe (like the Q.Peak Duo) produces 38 g CO_2e per kWh of electricity produced [89]. This number represents the emissions produced over the full lifecycle of the panel: from sourcing materials, to manufacturing the panel, to transporting and installing it, and finally disposing of it. It is worth noting that the data for emissions from fossil fuels only account for the emissions

[15] See Table 3 in Chapter 1.3 and Table 13 in Appendix A for more information.
[16] See Table 5 in Appendix A for a breakdown of array prices by size.

from physically burning the fuel – not mining and refining the fuel, transporting it to where it's used, or any of the other factors that are included in the solar life cycle assessment. This is not only an obnoxious double standard but also obfuscates the fact that the actual carbon footprint of fossil fuels is much higher than the numbers presented. However, in keeping with industry norms, the full life cycle carbon footprint of solar will be compared to the emissions from burning fossil fuels (see Table 9). Clearly, even accounting for the life-cycle carbon produced by solar panels, there is massive environmental benefit to be had from switching to solar energy. PV could save Lewiston 79% of its GHG emissions created by electricity use and, in doing so, save over $11,000,000 in terms of social costs of climate change.

g/kWh CO_2e From Solar	Energy Produced by Improved Model (kWh)	CO2e Produced (tonnes)	CO_2e Savings (tonnes)	Social Cost Savings[17]
38	372,623,000	14,200	52,300	$11,501,000

Table 9: GHG emission reductions and associated financial savings from installing solar.

Though the predicted amount of electricity that rooftop solar could create is more than enough to meet Lewiston's needs, it is highly unlikely that even a majority of building owners would install solar panels of their own volition. More hurdles to the implementation of solar, and the other technologies discussed in this study, can be found in Chapter 4. Additionally, as discussed in Chapter 1, using one technology to generate all of the city's electricity makes the energy system needlessly vulnerable. To put it colloquially, relying exclusively on solar power is like putting all of your eggs in one basket – and that basket resides in an increasingly unpredictable climate regime. Lewiston has many different resources besides solar that should be factored into future energy planning in order to create the safest, greenest, cheapest, and most resilient grid possible.

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[17] See Chapter 1 for more information.

Chapter 3.2: Harnessing the Power of Drinking Water

Frankly, Lewiston is not the optimal city for conduit hydropower. Lewiston's water supply system is very well planned and the city's topography isn't variable enough to warrant much pressure reduction, which is the primary means through which CHP is captured. However, this does not preclude the city from generating a significant amount of power from its water system. Even WSS' with little excess pressure can generate hundreds of homes' worth of electricity, making conduit hydropower very appealing for financial and environmental reasons.

Water distribution networks are critical systems, meaning that data about them is tightly controlled to ensure the safety and security of the water supply. Because the specifics of the water system are protected, the calculations in this chapter are very rough estimates. I cannot say with perfect certainty that Lucid turbines would be applicable in the intake pipe, and I may well be missing other places where in-pipe turbines could be deployed. That being said, this section will present one potential CHP deployment scenario based on the best publicly-available data.

Lewiston has 1,100 feet of 48-inch diameter intake pipe from its water source at Lake Auburn, which is a potential site for a series of Lucid turbines [68, 90]. Lucid's 50 kW, 48-inch in-pipe turbines are best installed in a series of 4 turbines along 50 feet of pipe, creating an installation with a total capacity of 200kW [68]. The available pressure head in the pipe dictates the amount of energy that will actually be generated. For example, an existing 4-turbine setup in a 48-inch pipe in Portland, Oregon produces 900 MWh per year based on the available 20psi of pressure, providing 51% efficiency in the field [61]. This is in line with existing estimates of hydropower efficiency. An installation in the intake pipe under the same conditions as the Portland turbines would cover .5% of Lewiston's electricity usage. Though this is not as sensational as the potential for solar in terms of covering demand, it is still significant. An installation providing 900 MWh per year would power 135 of Lewiston's homes. The same installation with next-generation turbines, which produce twice as much power, would cover 270 homes.

This power, naturally, comes with financial savings. At an LCOE of 5 to 12 cents per kWh, Lucid's Portland installation provides power at a significantly cheaper cost than grid electricity prices [61]. At the high end of the LCOE range – the most expensive scenario – conduit turbines would provide 14% cheaper electricity than the current residential grid price. At the low end of the LCOE range, the turbines would provide 64% cheaper electricity than homeowners are currently paying. Just in terms of cost to the end user, CHP turbines are more efficient than current electricity production methods.

Another interesting advantage of CHP turbines is that they can be financed like residential solar panels, meaning that installation can result in no cost to the city or water utility. The $1.7 million conduit hydropower system in Portland was completely privately financed and subject to a power-purchase agreement much like a PV system [61, 91]. The system is projected to generate $2 million worth of electricity over 20 years, and the profits from selling that electricity are shared amongst the city Water Bureau, the turbine company, and a private investor. After 20 years, the power-purchase agreement expires and the Portland Water Bureau gains the option to purchase the turbines and enter into a new power-purchase agreement [61]. Given that the expected life of a water delivery pipe with turbines is over 50 years, the purchase of this installation will result in profits on the order of $4.5 million for the Portland Water Bureau if they secure a similar power-purchase agreement to the current one. If Lewiston's intake pipe has more available pressure than Portland's, this figure could be higher.

CHP turbines also, of course, provide environmental benefits. Taking only GHG emissions into account, in-pipe turbines provide electricity with even less carbon per kWh than solar panels. No studies have been done to catalog the life-cycle carbon emissions of an in-pipe turbine. However, considering the extremely long life of a water delivery pipe, the durability of the turbines, and the accessibility of the materials used to make a turbine (compare the stainless-steel construction of a turbine to the silicon, titanium, boron, silver, copper, cadmium, etc. required to make a solar panel), the carbon emissions from in-pipe turbines are minuscule. With a conservative estimate of 5g CO_2e per kWh created over the turbine's lifespan, the next generation output of the turbine system presented above would only produce 8.8 tonnes of GHGs per year. In comparison, the modeled turbines negate 347 tonnes of GHGs per year – even after including the CO_2e generated by the turbines. In terms of the social cost of carbon emissions, the turbines save $76,000 per year.

Though harder to quantify, the concept of life-cycle analysis extends past GHGs into broader environmental impacts. CHP (and by extension MHP, which will be covered in the next section) have less environmental degradation and social justice impact associated with them than something like solar power due to the ease of obtaining the components that make up the technology. Stainless steel, which comprises the majority of an in-pipe turbine, is accessible, easy to make, and readily found compared to the rare materials and chemicals and extensive manufacturing process required to make solar panels. Additionally, CHP can lessen wear and tear on PRVs and other pipes in the WSS, reducing the frequency of pipe replacement and saving the emissions and environmental disturbance of creating, transporting, and installing new pipes. Of course, CHP cannot be the sole provider of electricity in the city, but the comparative environmental benefits that the turbines provide make conduit hydropower an invaluable part of a hybrid distributed renewable energy network.

Keep in mind that the above calculations cover only one instance where CHP could be implemented in Lewiston's WSS. The city also operates two 4.3 million gallon above-ground water storage tanks whose outflow could potentially be used for electricity generation with either Lucid or Kaplan turbines, as discussed in Chapter 2.3 [90]. Additionally, the WSS currently has one pressure reducing valve that is connected through 16-inch diameter pipes. Though the pipes are too small for a Lucid turbine, this could be an opportunity to install a Xeropex turbine as a PRV replacement or a Kaplan turbine to reduce pressure on the PRV, extending its operational life. There is also a potential for recovering energy at the water treatment plant using Kaplan turbines. Unfortunately, specifics are not available on the electrical output or cost of these turbines due to information constraints. The estimates presented in this section prove that conduit hydropower on any scale is a good financial and environmental investment.

Chapter 3.3: Capitalizing on the Canals

Lewiston is no stranger to distributed hydropower. They're well hidden, but there are 5 hydropower plants with a combined 95 megawatts of capacity are scattered around the city, currently providing power to the grid [92]. This is an amazing amount of power: enough already to cover the estimated electricity needs for both residential and commercial buildings. However, there is more opportunity in the city for hydropower development that does less harm to the environment than the existing dams. In fact, the Federal Energy Regulatory Commission (FERC) already outlined several locations on the canals for microhydropower development.

The water rights for hydropower generation in the city are complex, as rights to the energy of the Androscoggin River are partitioned between entities. The city owns the rights to the first 4.2 m^3/s of river flow, which is partially directed into the canal system [93]. Brookfield Renewable owns the next 232.2 m^3/s, which it uses to generate power at the 28.4 MW Charles E. Monty hydropower station at Great Falls on the Androscoggin. Lewiston then has rights to the next 15.6 m^3/s. However, seasonal fluctuations in river height mean that the full 15.6 m^3/s of water is only available for 5 or 6 weeks of the year, making it hard for the city to put to use [93].

Several defunct dams on the canals exist, including the Red Shop and Hill Mill structures on the lower canals (see Appendix B for a map of the canal system). In the past, Lewiston used the additional 15.6 m^3/s to generate power at the entrance of the canal system using 3 turbines housed in the city's Upper Androscoggin generating station. However, the fact that electricity prices fell dramatically – the original Upper Androscoggin power purchase agreement with Central Maine Power paid the city 12 cents per kWh, but when the contract expired they would only pay 5 cents per kWh – and the existing variability of the river flow meant that the turbines' maintenance costs eventually outweighed the profit from the energy created [93]. The final nail in the coffin was damage to the last remaining functional turbine from Hurricane Irene in 2011 [93]. This experience makes the city understandably hesitant to invest in hydropower. However, the following analysis will show that implementing microhydropower (MHP) in the city's canals represents not only a profitable but also an ecologically and socially sound investment as well.

The following calculations are best estimates using head data from FERC (see Appendix B), industry standard equations for potential capacity and generation, and the best current models for turbine prices [52, 59]. 5 potential MHP sites in the canal system were identified and visited. All are sites identified by FERC as having an acceptable head for hydropower. The sites are all suited to both Archimedes screws and Kaplan turbines. Crossflow turbines could potentially be installed as well, but the simplicity and economic advantage of Archimedes and Kaplan turbines make them a better fit for the city. Given the scarcity of scholarship on Archimedes screws for electricity generation, the estimates below are constructed to apply to both Kaplan and Archimedes turbines, with unknowns noted. Should MHP be implemented, more specific studies of each site must be completed to determine which turbine is best for the location. Archimedes turbines are preferred due to their minimal impact on the aquatic environment.

The following equation was used to determine generation capacity at each of the identified locations:

$$generation\ capacity\ =\ head * turbine\ efficiency * water\ density * gravity * discharge$$

[52]. This relatively simple calculation can estimate the potential hydropower generation at any location in the world. An 86% efficiency is assumed; this is the highest efficiency recorded by an Archimedes turbine and a somewhat low efficiency for a Kaplan turbine, which provides an acceptable estimate of power generation regardless of the type of turbine installed. Because water density changes with temperature, the number used in the equation is was assumed to be 999.75 kg/m^3, the density at Lewiston's average yearly temperature of 46 degrees. Head changes depending on the location of each turbine, but discharge at each station will be the same because flow through the canals is regulated. Total generation over the course of a year was modeled on existing hydropower projects, which, on average, actually produce 50% of their maximum possible generation [94, 95].

Estimating turbine price is much more complicated. Firstly, the best available equation models only the price of the turbine itself; the equation accounts for the cost of both mechanical equipment and electrical equipment but does not include the price of installation [59]. The price of labor and materials required to install each turbine can vary wildly depending on location and the scope of work to be done, so it is extremely difficult to model. The cost equation also differs by turbine type; unfortunately, no comprehensive studies of Archimedes turbine price have been completed. It has been found that Archimedes screws tend to be cheaper than other turbine types due to the fact that they do not need to be built to withstand full, pressurized immersion and there is no filtering mechanism required. Therefore, though it is the best available model, the following estimates will probably overestimate the cost of an Archimedes screw. The equation for predicting the price[18] of a Kaplan turbine is:

which gives an average error of 8.1% when compared to the cost of existing Kaplan turbines [59]. The head is related to the topography of the canal, so it is assumed to be constant as the

$$cost = 139318.161 * head^{0.02156} + 0.06372 * discharge^{1.45636} + 155227.37 * projected\ capacity^{0.11053} - 302038.27$$

other parameters change. The cost of the turbine falls as the projected capacity and discharge change and, additionally, the capacity increases with increases in discharge. This is critical because it means that small increases in river flow cause larger increases in capacity and decreases in the cost of the turbine.

Lewiston, which acquired the rights to the canals in 2018, has full control over the amount of water in the canals [96]. Currently, approximately 1.4 m^3/s of the city's original 4.2 m^3/s flow through the canals solely for aesthetic purposes [93]. This is more than enough water to implement MHP; most systems only require 1 m^3/s to be effective. However, the city could theoretically divert all of their allotted 4.2 m^3/s of river flow into the canals. Should they decide to do this permanently, the turbines can be resized, increasing generation capacity by a third and decreasing turbine costs per kWh generated by 44%. Archimedes screws are able to generate power at just 5% of the maximum discharge, allowing the city to vary the flow in the canals if

[18] This gives the sum in euros; all estimates have been converted to dollars using the February 2019 exchange rate.

desired [94]. Due to the fact that they must be constantly submerged, the larger Kaplan turbines are less well suited to variable flows. The turbines would have to be designed specifically to accommodate fluctuations or just be turned off when the canals are not running at 4.2 m^3/s.

At the current discharge through the canals, installing MHP at all 5 identified sites would yield a capacity of 400 kW and provide around 1800 MWh of electricity per year, covering 1% of Lewiston's current yearly electricity usage[19]. With the full 4.2 m^3/s, the turbines could have a capacity of 1210 kW and generate 5400 MWh per year, covering 3% of the city's electricity usage. Even with the large amount of hydropower currently produced, Lewiston has a significant resource in MHP on the canals.

Fortunately for the city, these turbines are all estimated to be much cheaper than the $1.7 million required for the conduit hydropower system discussed in the last section. The total cost for the proposed 400 kW system composed of 5 MHP turbines built for 1.4 m^3/s is estimated to be $534,000. If Lewiston decides to increase discharge through the canals and invest in a larger 1210 kW system, the price for all of the turbines would be $718,000 – triple the electricity with only 34% higher costs[20]. Again, these estimates only include the cost of the turbine itself, not labor or installation, which will definitely add expense. Many of the sites already have buildings on them – either old mills or defunct hydropower stations – which would have to be demolished or modified to incorporate new MHP turbines. It is difficult to determine if the existing infrastructure inside the buildings would reduce installation costs by allowing a retrofit or if that infrastructure would require the entire building to be replaced to accommodate the new turbines, which would increase installation costs.

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[19] See Table 14 in Appendix A for more information.
[20] See Table 15 in Appendix A for more information.

Though there is not much data on MHP financing schemes, there is no reason why this cost cannot be shared amongst the city, the utility, and/or private investors, much like the case study from Portland, Oregon discussed in the last section. Additionally, the city already has experience in hydropower financing from the Upper Androscoggin hydropower project.

As always, implementing MHP comes with significant environmental benefits. Considering that MHP turbines are constructed similarly to in-pipe turbines, 5 grams of CO_2e is an acceptable estimate for lifecycle GHG emissions produced per kWh. Accounting for this, turbines sized for 1.4 m^3/s discharge would produce electricity that negates 1,400 tonnes of GHG emissions per year and saves $300,000 in the social cost of carbon emissions per year. At 4.2 m^3/s, those numbers are tripled to 4,000 tonnes of GHGs and $900,000 saved. Additionally, if Archimedes turbines are used, these savings come at no hydrological or ecological cost to the local environment. The turbines would be sited in places where structures often exist, meaning that they will not meaningfully alter the landscape of the city. In fact, one of the many advantages of Archimedes turbines is that they can be open to the air and can, therefore, provide a new point of interest for locals and visitors.

Microhydropower generation in Lewiston's canals offers significant energy generation potential, a relatively low cost to build and operate, and large environmental and even aesthetic benefits over traditional hydropower projects. Microhydropower, if done correctly, is worth it, even in a lower income city.

Chapter 3.4: Heating in the Maine Winter

The previous three sections have quantified potential electricity production and compared it to Lewiston's current use. It is certainly important to know that the city's buildings can be 100% renewably powered from the 2017 baseline, but this does not mean that the city is fully powered by renewable energy. As previously stated, Maine relies predominantly on fossil fuels for heating, which consumes a large amount of energy and creates a massive source of GHG emissions and economic burden. However, it is entirely possible to heat the city with electric heaters powered by Lewiston's local renewable energy. The following analysis only includes residential buildings, as information about the heating requirements of commercial spaces not recorded by any agency. The estimates below are extremely conservative; it is entirely possible that the city could heat some or all of its commercial space with renewable power produced within city limits. As with electricity production, industrial spaces offer different opportunities for sustainable heating that will be briefly discussed in Chapter 4.2. In order to accommodate the widest variety of spaces and building types, the following calculations include both air source heat pumps and electric resistance heaters. The ASHP estimates are taken from real-world data on existing heat pumps in Maine, provided by Revision Energy, a leading installer of heat pumps in the region. The resistance heaters are assumed to be 1kW units, the most common commercially available type.

These calculations only include retrofits of existing residential buildings. New buildings will hopefully be heavily insulated and built for electric heating, reducing the size and number of ASHP and resistance heaters needed. Because existing buildings haven't been built to accommodate electric heating, the calculations assume that the average house will be relatively inefficient, requiring two heat pumps and two electric resistance heaters to heat areas that are not reached by the ASHP systems. Apartments in small apartment buildings are assumed to require 1 heat pump and 1 resistance heater because they tend to be larger and each apartment has more outdoor walls compared to apartments in larger buildings. Apartments in larger apartment buildings tend to be smaller and share more walls amongst themselves, which helps keep all of the apartments warmer, so they are assumed to require only one heat pump. Mobile homes and other buildings are hard to account for, so two electric resistance heaters are assumed to be appropriate as they can be portable or permanently installed and are applicable in a variety of spaces[21]. This is an overestimation of the heating equipment that would actually be installed in each type of home, though each building must be individually assessed to determine the best heating system for that individual space. It is difficult to predict if Lewiston's housing stock tends to be more open-plan, which favors ASHP, or more closed off, which is less efficient, so overestimation ensures that all layouts and types of buildings are accounted for.

Revision Energy estimates that the average heat pump in Maine will use between 2,500 and 3,500 kWh to keep the average home hospitable for an entire year [79]. This includes both the heating and air-conditioning modes of ASHPs and will change over time as the world warms. Taking the upper bound of electricity consumption, the 23,000 heat pumps required by the model will use around 81,400 MWh of electricity per year. Assuming that the average resistance heater uses 5,500 kWh per year – they're 2.5 times less efficient than ASHP but also likely to be turned off more often – the 20,000 electric resistance heaters will contribute around 111,000 MWh of demand per year. In total, 192,000 MWh will heat and cool all of Lewiston's modeled residences for a year. It is very likely that, in reality, residential temperature control will require less electricity, especially as climate change progresses and extremely cold winters become less common.

This energy, bought at current grid prices of $0.14 per kWh, would cost Lewiston $27 million per year. In Maine, the electricity required by the average heat pump costs between $360 to $500 per year and the idealized resistance heater included in the model would cost $770 per

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[21] See Table 16 in Appendix A for a breakdown of the model by home type.

year [79]. This calculation predicts that the electricity to heat the average home in the model would cost $2,550 per year. This is an intentional overestimation; Revision estimates that heating the average well-insulated home with grid-tied ASHP will cost just $1,706 per year [28]. Provided by local distributed renewable energy, this number would be even lower; heaters powered predominantly by solar electricity would provide the same amount of heat for $1,023 per year [28]. In any situation, including the most conservative estimate, heat pumps are more economical than heating with any fossil fuel [28]. The most expensive estimate for electric heating is $87 cheaper than heating the same house with natural gas, the cheapest fossil fuel heating method [28]. Revision's predicted electric heating cost is $881 cheaper than natural gas.

That being said, the initial upfront investment for an electric heating system is significant. Each heat pump costs around $5000 per indoor unit, including installation [79]. Resistance heaters cost between $100 and $400 per unit; most can be installed by the homeowner, though some wall-mounted units may require wiring by a professional. Each resistance heater is assumed to cost $500 including installation. The total cost of outfitting every residence in Lewiston with the equipment prescribed by the model would be around $126 million. Including the rebates offered by Efficiency Maine outlined in Chapter 2.4, the price drops to $101 million. The savings for the average Lewiston house, which is currently heated by heating oil and could be heated electrically for Revision's estimate of $1,706, would pay off the initial $5,000 investment in an ASHP system in just 4 years. Even though ASHP systems don't have financing schemes like rooftop solar arrays that make them as immediately financially advantageous, they are economical in the long run.

This is especially true considering the carbon emissions that implementing electric heating will save. ASHP's lifecycle carbon emissions are roughly 126 g of CO_2e per kWh, taking into account the production of all of the materials used to build the heat pump, the production and leak potential of the refrigerant used, and the energy required to safely dispose of the material [15]. ASHP's lifecycle carbon footprint is higher than the electricity generators due to the global warming potential of the refrigerant; when it leaks or escapes as the heat pump is dismantled, it acts as a greenhouse gas. The damage caused by the refrigerant constitutes 85% of the lifecycle carbon footprint. Therefore, the emissions of a resistance heater can be reasonably estimated as 15% of the emissions of an ASHP, as they are made of similar materials but do not contain the same types of refrigerants. With these estimates, electrically heating all of Lewiston's homes would emit approximately 12 tonnes of GHGs per year. Lewiston's current methods of heating, as laid out in Chapter 1.1, produce 71,000 tonnes of GHGs per year – electric heating would provide the same heat with 0.02% of the GHGs. This increase in efficiency will save $15,640,000 in future costs related to climate change.

This model is an extremely conservative case. In reality, it is very likely that far fewer heaters will be needed, so less energy will be required to run them and the greater the economic and environmental benefits will be. Even in this model, fully converting Lewiston to electric heating powered by electricity produced within city limits is entirely possible. It's even profitable; in any scenario, there is energy left over to sell to the wider grid.

This analysis has shown that all of the technologies outlined in Chapter 2 are preferable to the current methods of powering the city by any metric of comparison. Urban hybrid distributed renewable energy in Maine is not only technically feasible, but it is electrically, economically, and environmentally better than traditional methods of electricity and heat generation. However, this does not mean that the transition to renewable energy will be easy.

The next chapter explores potential barriers to implementing renewable energy, as well as opportunities to integrate the transition into other areas of the city.

Chapter 4: Other Considerations

This project has proven that it is technically possible to power and heat Lewiston's residences and businesses sustainably and economically while using only the resources found within city limits. This is not the end of exploration into the question of what it means to be a city of the future – it just scratches the surface. There are incredible technologies and advancements just over the horizon, as well as significant changes to the legal and social climate that will need to be adopted if the city is to actually implement renewable energy on the scales that science and justice demand. The above analysis provides a proof of concept; it can and should be refined and expanded as the industry and climate change advance. The myriad ways in which the energy and technologies detailed in previous chapters interact with other systems in the city and its ecosystems each provide opportunities and obstacles to the development of a truly sustainable and prosperous city. The following sections will outline a few of these potential limitations and opportunities, as well as areas of further study.

Chapter 4.1: Potential Limitations

Independence from fossil fuels is feasible in Lewiston; this does not mean that the transition can happen easily or quickly. The obstacles to just, timely renewable energy implementation are overwhelmingly political, which makes them both easier to plan for and harder to solve than physical problems. The only truly technical impediment to the transition is grid capacity. Simply put, the electrical grid is not set up to receive electricity from so many points in the city, especially with the type of variability that renewable resources create. Solar power generation fluctuates dramatically over the course of the day, which puts strain on the grid. Another study would be required to determine if Lewiston's infrastructure is capable of sustaining the variability of electrical supply and widespread distribution of renewable generation sites proposed in this paper. Storage can alleviate some of this problem; this study also assumes that the wider grid can act as a battery, which is not sustainable in the long term. Storage concerns will be addressed in section 4.2.

In addition to the infrastructural problem, distributing electricity necessitates long negotiations with entities that control the grid, be they corporations or municipal departments; in Lewiston, that entity is currently the Central Maine Power Company. In order for a generating station to be connected to the grid, an interconnection agreement must be reached with the utility transporting the electricity to customers. This agreement details how the owners of the generating station will interact with the transmission utility, including describing the required physical infrastructure connecting the station to the grid [97]. Fortunately, because the proposed generators are located in an urban area that is already fully connected to the grid, minimal new infrastructure needs to be built to connect the proposed generating stations compared to larger projects like hydroelectric dams and wind farms, which tend to be located farther from existing electrical infrastructure. However, interconnection agreements and the physical connection of the generator to the grid still need to happen. For rooftop solar installations, the company installing the array will negotiate this as part of the process [32]. Unfortunately for MHP and CHP projects, there are currently no interconnection standards specific to small hydropower systems, meaning that each contract must be customized to the specific generator [98]. This process adds time and money to each project's budget.

Once the generator is physically connected to the grid, the electricity produced must be bought by the utility, which requires the adoption of a power purchase agreement. The negotiation of these contracts can take time and incur legal fees. Each has an expiration date, usually after 20 years, at which time the price of the energy produced is renegotiated based on electricity prices [98]. Like the story of the Upper Androscoggin generating station discussed in Chapter 3.3, the expiration of a power purchase agreement can spell doom for a project, even if it is still producing the same amount of power at the same price as when the contract was first signed. This is not a reason to forgo renewable energy but something to keep in mind when developing and regulating projects.

In addition to the issues associated with connecting to the grid, each technology has issues associated with it that make it more difficult to implement. None of these issues are technical or economic – they exist in the social-political realm, which makes them tricky to deal with. One problem with rooftop solar in Lewiston is the number of rooftops provided by apartment buildings. In these cases, it falls upon the building owner to install the panels and decide how to distribute the benefits; tenants often have no power to install panels themselves. Some cities have pioneered multitenant solar financing systems; Virtual Net Metering, used in San Francisco, provides a way for the energy produced by the panels to be allotted to individual apartments, which helps post-installation but does not assist with getting panels installed in the first place [99]. GRID Alternatives, a socially-minded solar installation company based in Oakland, California, assists with negotiations with landlords and installation of the panels to help tenants get solar [100]. No programs like this exist in Maine, which creates an obstacle to installing solar on the large number of multitenant roofs in Lewiston.

Additionally, though the long-term cost-effectiveness of solar panels has been proven and financing plans requiring zero upfront investment are readily available, many people still believe that the payback period for a solar array is too long or installations are just simply not profitable, especially in Maine’s climate [101]. While public perception of the desirability of solar panels will get better with time as older installations start to become profitable and solar panels gain more social cachet, relying on an organic shift in attitudes will not lead to the speed or amount of adoption that is necessary to power the city and stave off climate change. This belief can seriously hamper the pace and extent of solar power's spread across suitable rooftops. This problem also affects microhydropower at the local level; due to the city's past experience with hydropower generation, they are reticent to invest in any more projects [93]. However, as the above analysis has shown, microhydropower is economically, environmentally, and energetically viable in Lewiston with the volume of water that the city has rights to. Unfortunately, this does not mean that the city will find the data convincing enough to undertake a new MHP project.

Microhydropower and conduit hydropower also face a different problem: regulation. MHP and CHP plants are regulated and licensed by the Federal Energy Regulatory Commission and the state of Maine individually. Even though they have minimal environmental impact, the projects each still have to prove that they will not meaningfully impact the natural or human-made environment – to standards set by 10 different federal laws requiring 10 different approval processes [98]. Though the licensing process for MHP and CHP projects was streamlined at the federal level by the Hydropower Regulatory Efficiency Act of 2013, Maine's hydropower licensing process is extremely complex due to the long history of hydropower in Maine and the large number of operational hydropower projects [98, 102]. In all, the licensing process for an MHP or CHP project involves working with at least 11 federal and state agencies as well as utilities. A study of licensing in Maine found that the average cost of the licensing process ranges from $100,000 for small projects into millions of dollars for larger or more controversial projects [98]. The regulatory burden on MHP and CHP projects in Maine is much higher than that of any other type of electrical generation technology, including fossil fuel generators [98]. This can discourage investors and consumers from pursuing hydropower.

Heat pumps are popular, available, and not heavily regulated, but, much like solar, they come with a significant initial investment. Fortunately, they do not face the stigmatization of solar panels, so more people are willing to try them. Though ASHP systems pay for themselves within 7 years, the entire upfront cost of the heater and installation falls on the homeowner. Because they don't produce energy, companies do not offer financing plans on the scale of solar arrays. This is a huge problem in a city like Lewiston, which has a median yearly income of $39,890 [4]. The $4,500 required to install a heat pump with Efficiency Maine rebates could be prohibitively expensive for many in the community. Additionally, houses must be well insulated for heat pumps to work effectively. For under-insulated homes, which describes most of the older homes in Lewiston, increasing insulation will save money in the long term but will be an additional burden on the homeowner. These additional costs will make large scale adoption of ASHP difficult.

Aside from the grid capacity problem, none of these issues are technological, environmental, or even economic, as all technologies are profitable in the long term. All of the problems can be solved through appropriate incentives and government action. State and local tax breaks and rebates are necessary to spur adoption of renewable energy by homeowners, landlords, tenants, and private companies to ensure that it is implemented on a timescale consistent with the most current climate science [1]. This will be especially relevant if the federal government continues to decrease federal tax incentives for renewable energy. Fortunately, the state of Maine recognizes the necessity of decarbonizing the energy system as a key economic, public health, and environmental issue. Several bills have been introduced in the 2019 Maine state legislative session to incentivize solar and other forms of renewable energy, though they face opposition [103, 104]. Additionally, the state has carried out studies to determine how to reduce the regulatory burden on MHP and CHP projects, though action on that front has been slow [98].

Government incentives work: Efficiency Maine, a quasi-state agency under the Public Utilities Commission, offers incentives to home and business owners for installing ASHP systems that have spurred the installation of 30,000 heat pumps across the state [80]. They also offer rebates for different types of building insulation, though the rebates are set up to encourage a transition to natural gas heating at the same time, which is counterproductive to the goals of creating a sustainable energy system and lowering energy prices [105]. The insulation rebate will have to be reworked to incentivize adoption of electric heating over all types of fossil fuels. These rebates are a small cost to the state in comparison to the millions of dollars they will save in heating costs, public health expenses, and the future impacts of climate change. Maine is moving in the right direction on renewable energy; however, more incentives and a restructuring of regulations will be required to encourage the adoption of these technologies on the scale required to make a full transition to renewable energy.

The final, overarching political barrier to the encouragement of renewable energy is the existing energy system's preference for conventional fossil fuel energy. The incentives proposed in the previous paragraph pale in comparison to those already received by fossil fuels; the entire energy market is distorted in their favor. Trade barriers and taxes increase the price of renewable energy, but the most insidious problems are the ones that artificially decrease the price of fossil fuels [10]. As the discussion of life-cycle carbon analysis in Chapter 3.1 alluded to, fossil fuels typically receive special treatment in comparisons with renewable energy. This doubly true of how the energy market prices different fuels. Non-consideration of externalities, which is at the core of the double standard of lifecycle carbon emissions, and governmental preference in the form of subsidies given to conventional energy artificially lower the price of fossil fuels and dangerously obfuscate the damage they cause [10]. The fossil fuel prices shown in this study are only nominally correct; they reflect the price of the fuel on the market at the time but do not reflect either the actual price of the creation of the fuel itself or cost of the damage it creates. The non-consideration of externalities like climate change, environmental degradation, and public health impact in the prices of goods afflicts all sectors of the economy. This method of valuation must be changed in order to create a truly sustainable society, but the process will be much slower and more involved than simply addressing subsidies [10]. Currently, fossil fuels and the companies that dig them up are given subsidies by governments that make fuels' final price cheaper than it would otherwise be. In 2013, the U.S. alone provided $0.6 trillion dollars to subsidize fossil fuels. In 2015, the world paid $5.3 trillion: 6.5% of the global gross domestic product (GDP) [106]. Subsidies are ostensibly given out of a desire to make energy, which up until recently was almost entirely fossil fuel-based, more accessible to poorer populations. However, this practice ends up benefitting only high-income groups and does trillions of dollars of damage to the environment and public health, which disproportionately affect lower-income and marginalized groups [106]. In 2013, simply eliminating fossil fuel subsidies and allowing the market for fossil fuels to reflect the price they actually cost would have reduced global GHG emissions by 21%, fossil fuel-caused air pollution deaths by 55%, and raised total revenue by 4% of global GDP and economic welfare by 2% of global GDP [106]. Removing subsidies in the federal and state energy markets and including consideration of externalities, just like implementing renewable energy, is economically, ethically, and environmentally advantageous. However, efforts to change the subsidy regime – or incentivize renewable energy, or just free the energy market to allow more competition from renewable energy sources – have been and will be met with fierce resistance from the fossil fuel companies used to a favorably skewed market [10, 106]. This resistance comes in the form of lawsuits, massive donations to fuel-friendly politicians, disinformation campaigns against renewable energy, and many other guises [107]. The fossil fuel industry will doubtless be a major obstacle to implementing renewable energy on a statewide or national scale.

There are a wide variety of obstacles, from the extremely local to the overwhelmingly global, that will make the implementation of renewable energy on any scale difficult. Local efforts to source more sustainable energy are intricately linked with national and global political-economic systems, meaning that no obstacle is irrelevant to even this small project. On any scale, the transition to renewable energy and all that it necessitates will have to be done with a consideration of social justice and protections for lower-income and more vulnerable populations. Fortunately, many studies have been done on this subject [106]. Science, economics, and ethics are clear about the way to proceed in order to secure a habitable planet; though it will be difficult, the obstacles outlined in this chapter and all those that are unforeseen must be overcome in order to implement renewable energy and bring about the society and city of the future.

Chapter 4.2: Opportunities and Interactions

Fully adopting renewable energy requires more than just installing solar panels and microhydropower generators. In order for the transition to happen fully, the many systems that interact with the grid need to be updated. There are also many other technologies that offer opportunities to make city systems more efficient, more electric, and more sustainable that fell outside the scope of this project. This section will briefly address some of these opportunities and interactions to highlight them as areas for further study. Due to the ever-advancing and highly innovative nature of the renewable energy industry, this will not be an exhaustive list; interested parties are encouraged to seek out the most current proven technologies and ideas for implementation.

The most important interaction that needs to be addressed is electricity storage and load, which is the demand for electricity over time. As previously discussed, the generators proposed in this paper do not produce electricity on the same timescale as traditional electrical generators. In the current electrical system, load drives generation. Electricity is consumed as it is created and supply must march demand to avoid blackouts. Traditional generators provide electricity in real time and can be switched on and off when necessary to ensure that there is always enough available electricity [108]. Currently, load is highly variable; it spikes in the morning and early evening, when people are at home running major appliances, and craters during the day and at night while people are at work or sleeping (see Figure 5 in Chapter 2.1 for a graphical representation). However, this is not how renewable energy works. Solar power, as discussed in Chapter 2.1, produces all of the energy required for the entire day in a very short amount of time and nothing for the rest of the day. MHP and CHP produce electricity relatively constantly; though they can be turned on and off, it is more efficient for them to be run constantly. This creates a fundamentally different, supply-driven electricity regime.

In order to truly power the city with the resources found in Lewiston, electricity must be captured and stored while it is being produced and then released into the grid when load outweighs generation. House-size batteries are becoming more common as a way for individual buildings to manage their solar power generation. However, relying on building owners to install batteries runs into some of the same problems discussed in the previous section, meaning that batteries will not be installed as completely or as quickly as required to make renewable-powered grid feasible. Grid-scale storage technologies such as large batteries, flywheels, pumped hydropower, and compressed air storage can alleviate this problem. In addition to ensuring that renewable energy can be completely integrated into the grid, grid-scale storage is also more efficient, more cost-effective, and more reliable than conventional methods of real-time generation [109, 110]. Each type of storage method has benefits and drawbacks, and a separate study would need to be completed to determine the best storage method for Lewiston.

Storage solves part of the problem, but in order to be truly efficient, load must be restructured to better match the profile of energy generation. Demand management can be partially accomplished through incentives like reduced electricity rates during peak generation hours, which encourage electricity use while it's readily available. However, to ensure that demand is managed over the long term, physical measures must be taken. The most comprehensive way to ensure this is through the implementation of a smart grid, which updates existing grid infrastructure with a combination of energy efficiency measures, smart devices that time their electricity use to peak generation times, and distributed hybrid renewable energy generation [111]. By ensuring that non-essential electric appliances (like washing machines and electric water heaters) run at times with excess energy instead of times with high demand, load can be shifted to better reflect generation and therefore reduce the size of the energy storage facilities required. Smart grids allow for better use of resources, which saves residents, governments, and utilities money and protects the environment. Both economic and physical demand-side management should be studied to ensure that the transition to renewable energy in Lewiston is as effective.

Plug-in electric vehicles (EVs) offer an opportunity to both manage load and store energy while decarbonizing transportation, another huge sector of city life and major contributor of

GHG emissions. Society cannot continue fueling transportation with fossil fuels, which are currently the only major fuel source for transportation of all kinds. Aside from the obvious pollution and climate impacts of fossil fuel-powered vehicles, they will not be economically feasible in the near future; EVs are currently almost cost-competitive in terms of initial investment and have much lower maintenance and fuel costs compared to conventional cars [112]. There will be a transition to electric mobility in the near future that offers opportunities for integration with a smart grid. These opportunities are predicated on the fact that the vast majority of cars are parked either at a house or workplace for most of the day. If each EV driver plugs their car in while it's parked and the charging stations are connected to a smart grid, cars can be preferentially charged when there is excess energy in the system, managing demand [113]. Additionally, the batteries in the cars themselves can provide additional electric storage capacity. Because EV batteries charge very quickly and are often not depleted over the course of a normal day's driving, that excess energy can be used to supplement the grid at night when most cars are parked and generation is lower [114]. Electric buses, which are already used in many cities, can also be used in this way. Future city and energy planning should account for EVs in order to integrate them into the fabric of the grid and of the city itself.

Industry is the last major sector of city life that needs to be addressed in order to create a truly sustainable city. Like electricity, heating, and transportation, industry offers myriad opportunities for renewable energy generation and interacts with many other city systems. Industrial systems were not considered in the main body of this project for two reasons: companies and governments don't publish data on electricity use or building characteristics, and, more importantly, because the opportunities offered by industrial settings are very different from those offered by residential and commercial buildings. For example, ASHP and resistance heating are not well suited to heating the cavernous interiors characteristic of industrial buildings. However, existing heating systems in these buildings allow for cogeneration, which can be implemented to create both heat and electricity for the building at the same time. Cogeneration uses waste heat created by the boiler and furnace to generate energy, meaning that fuel is used much more efficiently [115]. It is only economical to outfit large heating systems for cogeneration, which makes industrial buildings particularly well suited to this technology. Cogeneration can be used on any large furnace, meaning that centrally heated apartment and office buildings are also prime opportunities. Additionally, other industrial processes that require heating or generate waste heat, such as brewing, can be used for cogeneration; Sierra Nevada Brewing Company uses waste heat from the brewing process to generate steam for heating, which reduces load on the building's boilers and makes the whole operation more fuel-efficient [116]. The proliferation of breweries and revitalization of Lewiston's large downtown mill buildings provide potential opportunities for cogeneration.

Industrial heating systems can be made even more carbon-efficient by replacing the heating oil or natural gas fuel with a sustainable alternative such as renewable fuel oil (RFO). RFO is made from forestry and agricultural waste. It repurposes waste products from industries found in locally in Maine and reduces the emissions of a traditional large boiler by 70 to 90% over its lifetime [117]. Regardless of the type of fuel oil used previously, RFO can be burned with minimal adjustment to the existing heating system due to the fact that it has effectively the same qualities as number 2 heating oil and can be burned as a 50-50 mixture of RFO and ultra-low sulfur diesel to emulate number 6 heating oil [118]. Bates College, which is located in Lewiston, has already switched their steam-based district heating system to renewable fuel oil with great success; the boiler transition cost $200,000, the RFO costs slightly less than the heating oil and natural gas combination used previously, and the switch reduces the college's emissions by 3,000 tonnes of GHGs per year [119]. Heating with wood pellets and solid fuels made from waste from the timber industry are also opportunities to reduce GHGs and waste from heating and industry. Cogeneration and alternative fuels are just two of many improvements that can be made to make Lewiston's industrial sector more sustainable and more economically profitable. Each building's heating system would have to be studied to better understand the generation and efficiency opportunities offered by that particular location.

In addition to these considerations of the city system, there are opportunities in the field of renewable energy technology that can potentially allow Lewiston to generate more power and become more efficient. Effectively fighting climate change requires that we make do with what we have at the moment but also constantly look to the future. This paper focused on solar, microhydropower, conduit hydropower, and air-source heat pumps because they are scalable, currently available, and proven to be effective in urban contexts. Energy independence is possible with just these technologies, but, in the very near future, many more technologies will meet these parameters and be applicable in Lewiston to perhaps even better effect.

Hydrokinetic power is one such technology. Hydrokinetic systems are placed in the bottom of a river or bay, where the motion of the water moving past them spins the turbine and generates electricity [120]. The systems provide kilowatts of power and do not disrupt fish, boat passage, or the aesthetic landscape of the river, provided that they are sited in deep enough water. The Ocean Renewable Power Company, based in Portland, Maine, is currently testing a hydrokinetic turbine over winter in a town in Alaska. Preliminary results suggest that hydrokinetic power could be a great resource there and elsewhere [120]. A survey of Maine hydropower found that the Androscoggin River at Lewiston is one of the best places for hydrokinetic power deployment in Maine, judging by the river's depth and average discharge [98]. Once these turbines become commercially available, the city should look to add hydrokinetic power to its arsenal of potential renewable electricity generating technologies.

All of this is to say that this paper only measures a tiny portion of the potential for renewable energy generation in Lewiston. The four energy generating technologies considered in the study provide a good estimate of potential generation based on currently available technologies, but there are many other ideas, both known and not invented yet, that have the potential to help Lewiston generate heat and electricity economically while reducing its carbon footprint. There are also many ways in which the electricity generated by a hybrid distributed renewable energy system interacts with the rest of the city, which all have possibilities and pitfalls of their own. The transition to renewable energy will probably be one of the most planning-intensive, legally-fraught, and socially-charged projects ever undertaken by the city, but the alternative is much worse. The effort invested over the next few decades will pay itself back many times over and help ensure that all of Lewiston's residents, and all of humanity, have access to a healthy future.

Conclusion: The System in Practice

This study has proven that it is technically possible for Lewiston to produce enough electricity to power its residential and commercial buildings and heat its homes using only 4 currently available technologies and the resources found within city limits. Though the barriers to implementation are high, the transition to renewable energy has to happen in order to ensure long-term energy security and a safe, livable future for Lewistonians and people all around the world. The aim of this paper is not to convince the reader that this transition is necessary – the physics should be proof enough– but to move past the debate and investigate the other, separate benefits that come along with the transition. Sustainability does not have to, and should not, totally motivate the implementation of renewable energy; public health, energy security, social justice, and economic impact are all critical components of the transition and should be given ample consideration in order to ensure that the city of the future is not only sustainable but equitable for all citizens. Regardless of the motivation, implementing renewable energy is the way forward for cities large and small. This paper endeavors to provide a picture of what creating one such future city might be like.

The distributed hybrid renewable energy system modeled in the paper comes with a significant upfront investment: the sticker price for purchasing, installing, and permitting the entire system is $350 million, assuming that the regulation process for each MHP and CHP generator incurs $100,000 in fees. This price, including licensing, drops to $255 million when current state and federal incentives are accounted for. However, the city itself – including citizens and government – will bear only a tiny fraction of that cost. The widely-used investment strategies for funding the installation of solar power and CHP that split the cost to the landowner, or absorb it completely, can easily be applied to MHP. ASHP and electric heating systems, which contribute 37% of the estimated cost of the energy system, can be incentivized to bring down the installation price and reduce the burden on individual building owners. These measures allow for the burden of the upfront cost to be shifted to corporations and the state, which lets citizens reap the benefits of cheaper power and heating without having to sacrifice daily necessities to fund the creation of the network. This is especially critical in a lower-income community like Lewiston, which tends to be focused on day-to-day survival rather than future return [5]. Local and state governments, on the other hand, are charged with ensuring the long-term health and stability of the community, which makes renewable energy an attractive option. Taking into consideration the financing plans that reduce upfront cost and the timescales that governments must plan for, the long-term return on investment and environmental and public health benefits make the transition to renewable energy not just attractive but imperative.

Make no mistake; renewable energy is profitable in the medium to long term. Including different financing plans and assuming that power purchase agreements will reflect current grid prices, each distributed generator will produce enough energy to pay for itself in 20 years or less, at which time it starts providing essentially free energy. Additionally, with only the technology included above and the resources currently available, the modeled city can meet its calculated energy needs while selling an additional 27 MWh to the grid, which would generate $3.85 million per year at current grid prices. If the city government elects to increase discharge in the canals to the full 150 cubic feet per second it has rights to and waits to install CHP until the next generation turbines are available, the excess energy would be worth $4.75 million per year.

Accounting for climate impacts, switching to the system proposed would save 123,000 tonnes of greenhouse gases from being emitted into the atmosphere per year. This is not to say that renewable energy does not have any impact on the climate: the modeled energy and heat system produces 14,000 tonnes of GHGs per year based on the lifetime environmental impact of each technology. Solar panels account for 99.7% of emissions from the new system, owing to their relative abundance and their comparatively resource-intensive construction. For context, the current energy regime in Lewiston emits 138,000 tonnes of GHGs per year. Reducing the city's carbon emissions by 90% not only helps put Maine and the entire world on the track to avoiding climate catastrophe but it also saves $27 million per year in terms of damages incurred by the social cost of carbon emissions.

The results of this study provide an idea of the magnitude of cost and benefit associated with installing renewable energy in Lewiston. Wherever possible, real-world, local data has been used to make the data as accurate as possible to how the system described above would look in practice in Lewiston. However, it is entirely possible that, when the city decides to take the leap and become energy independent, the hybrid distributed renewable energy system actually installed will look nothing like what is described above. New technologies, and methods of installing and integrating them, will doubtless expand the potential for generation and decrease the consumption of the city, allowing Lewiston to export even more energy with even less environmental and economic cost.

Nobody knows exactly what the future will bring. We do, however, know that our actions today will dramatically affect our quality of life in the future. This study proves that powering a city with local renewable energy is financially and socially possible and environmentally imperative. With just four existing technologies and a complete dedication to ensuring the best possible future, Lewiston can provide sustainable, economically viable energy for all of its citizens and lead the world in becoming a city of the future.

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Appendix A: Additional Tables

Chapter 1 Tables

For 2017	Number of Customers	Total Use (MWh)	Average Use per Customer (kWh)	Total CO_2e emissions (tonnes[22])
Residential	16,063	106,700	6,643	41,600
Commercial	2,441	63,400	25,979	24,800
Total	18,504	170,100	16,311 (avg.)	66,400

Table 10: Summary of electricity use in Lewiston in 2017. Usage and price data is for Central Maine Power and customer data is from the Census [11].

For 2017	Total Use (kWh)	Total CO_2e emissions (tonnes)	CO_2 emissions (tonnes)	N_2O emissions (tonnes)	SO_2 emissions (tonnes)
Residential	106,700,000	41,600	23,600	58	63
Commercial	63,400,000	24,800	14,000	35	37
Total	170,100,000	66,400	38,000	93	100

Table 11: Statistics on GHG emissions from generating the electricity that Lewiston used in 2017 [11, 13].

Chapter 3 Tables

Array Size	Number of Roofs	Average Array Cost (before tax credits)	Average Array Cost (after tax credits)	Total Cost (before tax credits)	Total Cost (after tax credits)
0-5 kW	2,400	\$11,675	\$7,473	\$25,620,000	\$17,934,000
5-10 kW	3,400	\$23,638	\$16,546	\$80,368,000	\$56,257,000
10-15 kW	1,500	\$33,550	\$23,485	\$50,325,000	\$35,228,000
15-20 kW	705	\$45,750	\$32,025	\$32,254,000	\$22,578,000
20-25 kW	368	\$61,000	\$42,700	\$22,448,000	\$15,714,000
25-30 kW	184	\$76,250	\$53,375	\$14,030,000	\$9,821,000
Total	**8,557**			**\$225,000,000**	**\$158,000,000**[23]

Table 12: Average solar array cost for residential-size installations and the price to equip all available surfaces with panels. Based on [88].

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[22] 1 tonne, or metric ton, is equal to 2205 pounds.
[23] Rounded to the nearest \$100,000

	Lewiston's Energy Use (MWh)	Energy Produced in Improved Scenario (kWh)	Excess Energy (kWh)
Electricity	170,120,000	372,623,000	202,503,000
Price of Solar	$15,311,000	$33,536,000	$18,225,000

Table 13: LCOE predictions for a full adoption of solar power in Lewiston with all improvements applied.

MHP Site	Capacity at 1.4 m^3/s (kW)	Potential Generation at 1.4 m^3/s (MWh)	Capacity at 4.2 m^3/s (kW)	Potential Generation at 4.2 m^3/s (MWh)
Bates Weave Shed	100	460	300	1360
Red Shop	80	350	240	1050
Hill Mill	100	460	300	1360
Continental Mills	80	350	240	1050
Lower Androscoggin	40	190	130	580
Total	**400**	**1810**	**1210**	**5400**

Table 14: Estimated capacities and generation potentials at potential MHP sites. Calculations based on Elbatran et al. [52].

MHP Site	Cost at 1.4 m^3/s ($)	Cost per kW of capacity at 1.4 m^3/s ($)	Cost at 4.2 m^3/s ($)	Cost per kW of capacity at 4.2 m^3/s ($)
Bates Weave Shed	117,000	1,140	155,000	500
Red Shop	107,000	1,370	144,000	610
Hill Mill	116,000	1,140	154,000	500
Continental Mills	107,000	1,370	144,000	610
Lower Androscoggin	87,000	2,000	121,000	940
Total	**534,000**		**718,000**	

Table 15: Estimated costs of each MHP turbine based on Cavazzini et al. [59].

Building Type	Number of Residences	Heat Pumps per Residence	Resistance Heaters per Residence
House	7,740	2	2
Apartments in Buildings with 2-4 Apartments	3,567	1	1
Apartments in Buildings with 5-10+ Apartments	4,222	1	-
Mobile Homes and Other Buildings	534	-	2

Table 16: Residence types and appropriate heaters. Based on the American Community Survey and Revision data [12, 79].

Appendix B: Maps of Lewiston's Canal System

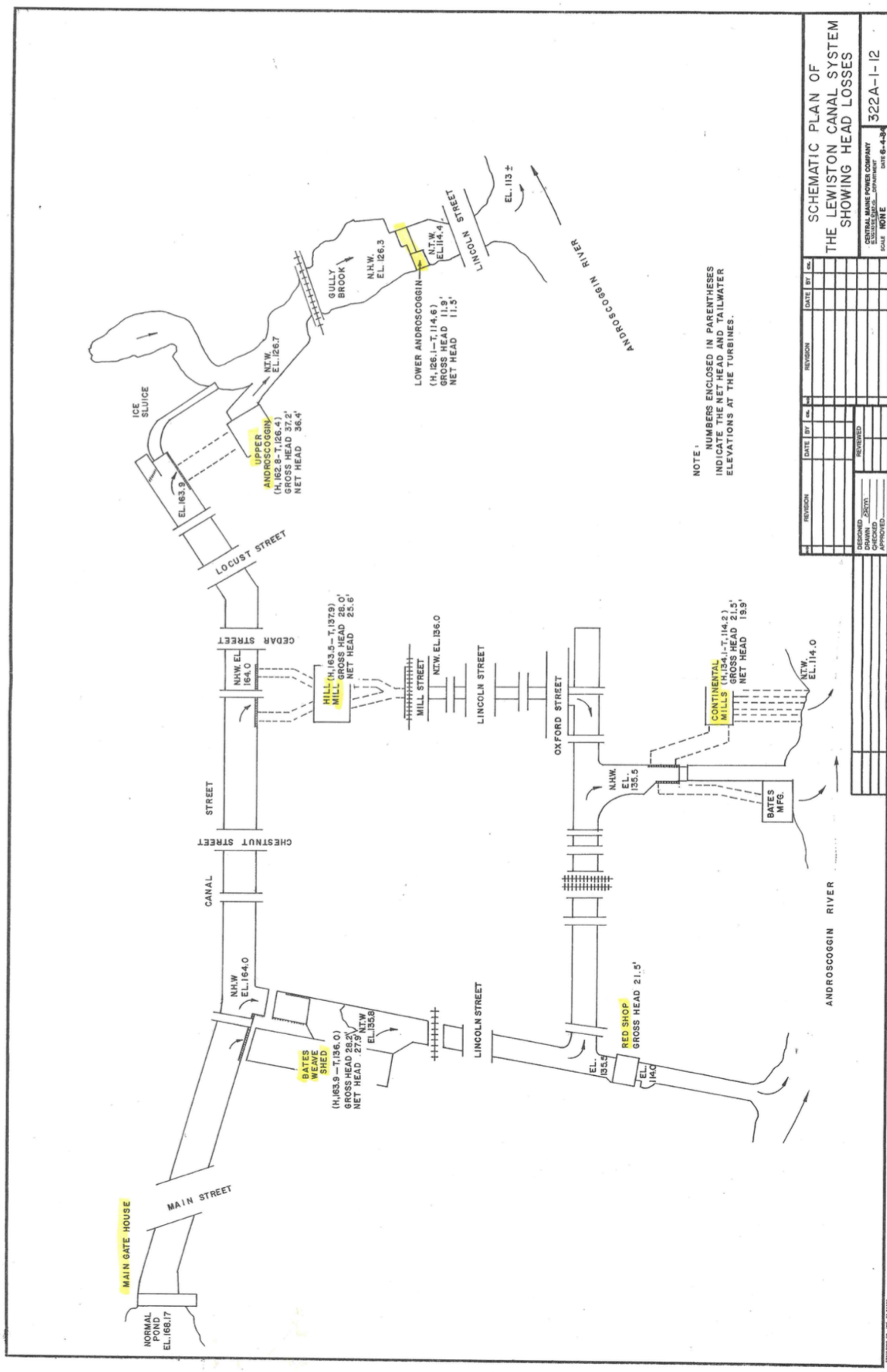

Figure 13: The complete canal system in Downtown Lewiston [93]. Proposed MHP sites are: Bates Mill Shed, Red Shop, Continental Mills, Hill Mill, and Lower Androscoggin.

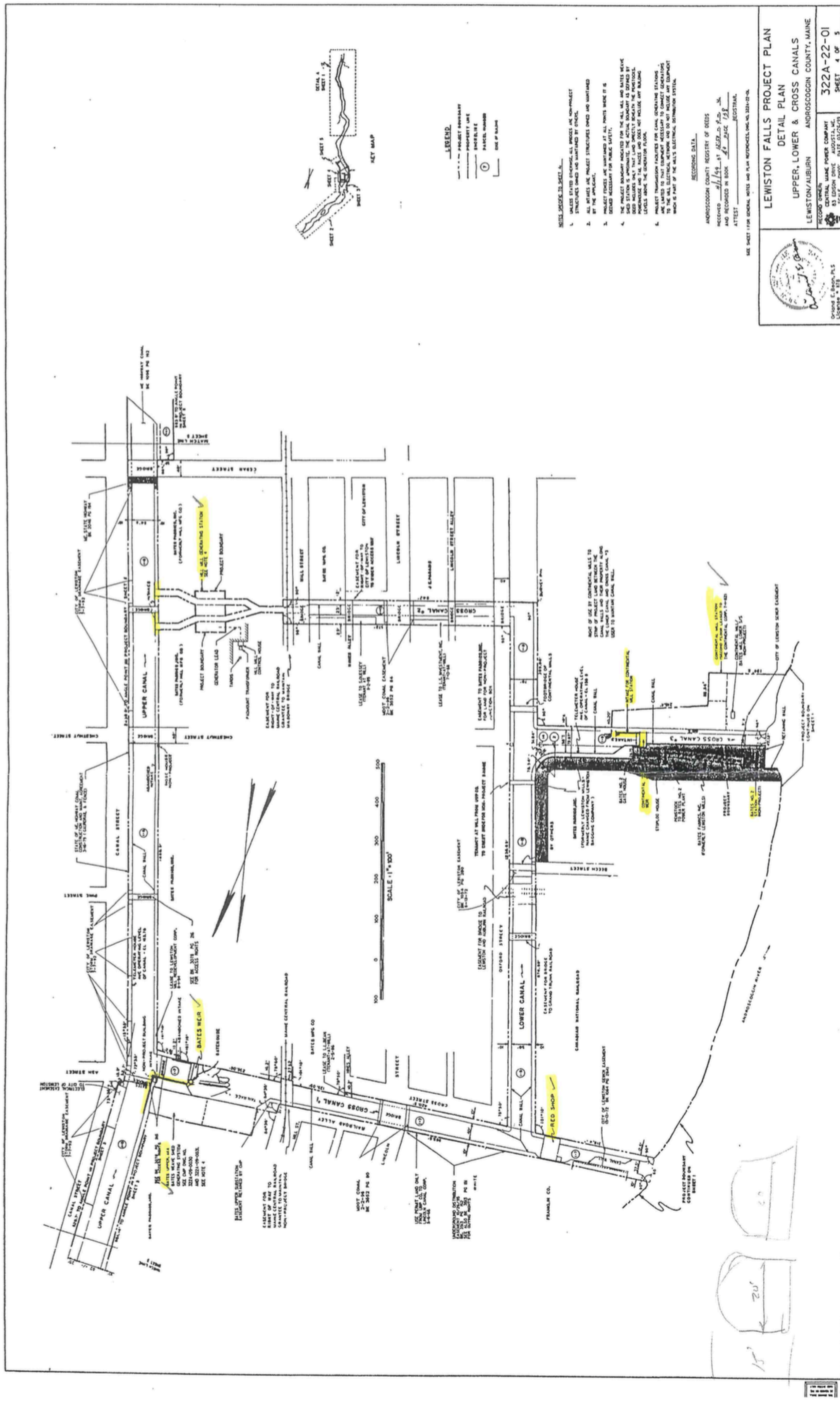

Figure 14: A more detailed view of the canals through the city and relevant features [93].

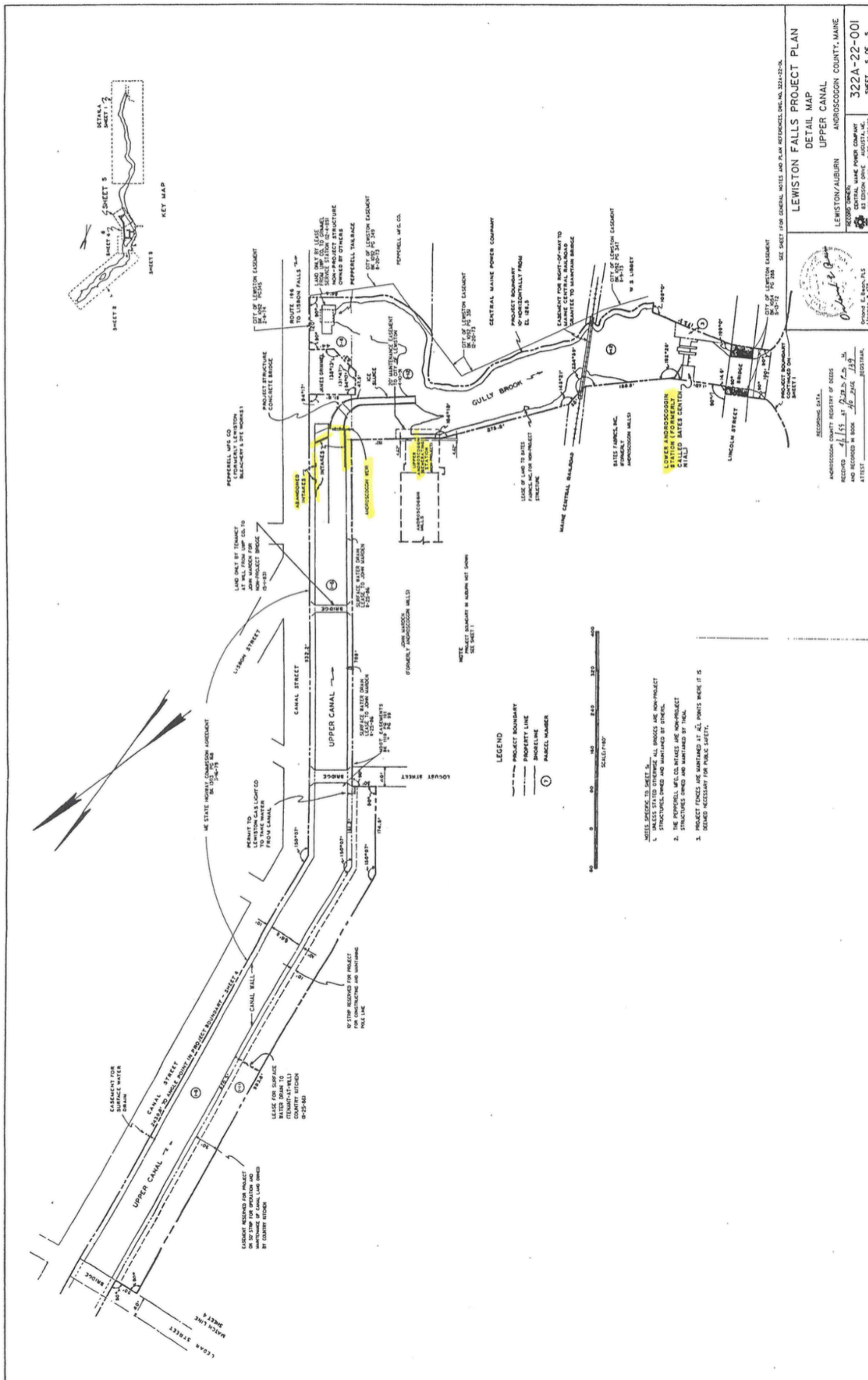

Figure 15: A more detailed view of the upper canal and its discharge back into the Androscoggin, with relevant features [93].

Appendix C: Detailed Methodology

This appendix lays out all of the calculations used to arrive at the specific conclusions presented in the study that were not provided in the text. It is intended to be general but show the sources of data used to create a model for Lewiston so that similar calculations can be replicated in other cities. Of course, the types of generators will differ based on the resources available in the city, but the basic methodology will stay the same. The calculations are presented conceptually; in practice, numbers will need to be converted to ensure that all inputs are in the same units before any calculations are carried out.

Chapter 1 Calculations

Electricity Use and Cost

Electricity use was calculated based on Energy Information Administration data for total sales and revenue by utility [11]. Residential and commercial figures were used. Average consumption and customer bill were calculated for clients of Central Maine Power Company by dividing total electricity sales, both in dollars and in MWh, to a class of customer by the number of customers in that class. These averages were multiplied by the number of residences and businesses, respectively, in Lewiston, using data from the Census [4]. Adding the results for consumption and cost provided totals for the entire city's electricity use and amount spent on electricity. Both the Census' Quickfacts viewer and American Factfinder were used to find information throughout this project. Data from the Census' American Community Survey [12] on the types of heating fuels used by homes in Lewiston and estimates on average heating fuel use from Revision Energy [28] and the Maine Governor's Energy Office [17] were used to calculate the total average heating fuel requirements of the city's residential buildings. Heating oil, natural gas, and propane were considered. Average heating fuel use by fuel was multiplied by the cost per unit of the fuel [13, 17, 18], then the fuel expenses were added to provide the total cost of heating fuel in Lewiston.

Baseline Emissions

Baseline GHG emissions for each heating fuel were calculated and then combined for a total. Emissions for a particular fuel were found by multiplying the average heating fuel use per home by the fuel's emission factor of a greenhouse gas [21]. CO_2, N_2O, and CH_4 were included. These emission factors for N_2O, and CH_4 were converted into CO_2 equivalents by multiplying them by their global warming potential [20]. All of the CO_2e amounts were then added to find the total GHG emissions for the average house burning that specific type of fuel. This is summarized in the following equation:

$$\text{Total CO2e emissions} = \text{total consumption} * [\text{CO2 emission factor} + (\text{N2O emission factor} * \text{N2O global warming potential}) \\ (\text{CH4 emission factor} * \text{CH4 global warming potential})]$$

This number was calculated for heating oil, natural gas, and propane – all of which have different emission factors based on their chemical composition. The average emissions per house for each heating fuel was then multiplied by the number of houses using the heating fuel, found in the American Community Survey, to give the total emissions per heating fuel. These were then added to create an estimate for total emissions from heating for all residences in Lewiston.

Baseline greenhouse gas emissions for electricity use in the city were estimated using the same equation, without the CH_4 term due to constraints on available information. The CO_2e intensity of Maine's electric grid, including CO_2 and N_2O, was calculated as above using emissions data provided by the Energy Information Administration [121]. This was multiplied by the amount of electricity used by the average home or business to find average emissions per home or business. Electrical GHG emissions were calculated separately for residential and commercial consumers to give a better picture of the average consumer in each category. These numbers were then multiplied by the total number of residences or businesses and then combined to estimate the total GHG emissions from electricity use in the whole city. It is important to note that there are many other greenhouse gases emitted by the process of creating electricity and heat in Maine, but agencies only keep data on two or three of them. In reality, emissions are higher, but this is the closest estimate possible with available data.

Chapter 3 Calculations

Solar Power

For solar power generation, the improved tilt angle scenario was calculated by first dividing the solar radiation received by a horizontal panel in Maine by the radiation received by a panel at 44%, as found on the National Renewable Energy Center Solar Resource Maps [42]. This predicted a 22% increase in radiation received by a tilted panel. The generation potential of only the flat roofs, as given by Project Sunroof [81], was multiplied by .22 and added to the total potential generation, as shown below.

$$\textit{Potential generation if flat panels are angled} = \textit{total potential generation} + (.22 * \textit{flat roof generation})$$

The other scenarios for solar power improvement were calculated by first removing the 15% panel and 85% inverter efficiency from the potential generation and maximum capacity given by Project Sunroof [81, 82]. The equation for generation is given below. Capacity was calculated the same way.

$$\textit{generation at } 100\% \textit{ efficiency} = \textit{total generation potential} \; / \; .15 \; / \; .85$$

For improved panels alone, the 85% inverter efficiency and the Q Cell Duo's 19.3% panel efficiency were added back in. The reverse was done with for the 99% efficient SolarEdge inverter alone, and the scenario with both the Q Cell panels and the SolarEdge inverter replaced both of the Project Sunroof model's efficiencies. The scenario with all improvements was found by dividing the tilted panel potential generation by the model's panel and inverter efficiencies and then re-introducing the Q Cell and SolarEdge efficiencies.

The cost of the solar installations was estimated using data on average solar installation price by size from Energysage [88]. Some prices were averaged to create an array of average costs that better matched the data from Project Sunroof (see Table 12 for an example). These average costs per installation size were multiplied by the number of installations of that size predicted by Project Sunroof to give the total cost of all of the arrays in each size category, then all of those costs were added to give the total cost for all residential-sized solar arrays. This was done for both pre- and post-tax credit prices from Energysage.

Savings from the current grid price were estimated using the LCOE. The total generation with all improvements, calculated above, was multiplied by PV's LCOE of $0.09 per kWh to estimate the total price of the solar power for one year. The grid price for the same amount of power was calculated by multiplying the total generation with all improvements by the average grid price of $0.14 per kWh. The LCOE price was subtracted from this to give total savings.

The greenhouse gas emissions from the PV arrays were calculated by multiplying the lifecycle carbon footprint of the panel, given in grams per kWh [89], by the total generation with all improvements. Because the total potential generation from PV is larger than Lewiston's yearly energy use, the GHG emissions from solar were subtracted from Lewiston's electricity emissions to give the total GHGs avoided per year from installing solar panels. The savings in terms of the social cost of carbon were calculated by multiplying the total emissions saved, in tonnes, by $220.

Conduit Hydropower

The conduit hydropower generation potential, in terms of houses powered, was found by taking the actual generation of the installed turbines in Portland, Oregon [68] and dividing it by the average electricity use per residence.

LCOE calculations were carried out in the same way as for solar power, using the LCOE given by Lucid [61]. Because the LCOE of conduit hydropower is a range, both the lower bound and upper bound costs were calculated. Savings were calculated in the same way as the solar power LCOE savings.

The total generation of conduit hydropower is lower than Lewiston's total annual electricity use, so GHG savings were calculated by first finding the emissions that would be created by sourcing the total potential generation of the conduit turbines from the grid using the CO_2e intensity calculated previously. Then, the conduit turbine lifecycle carbon footprint per kWh was multiplied by the total potential generation to find the GHG emissions from the conduit turbines. This number was subtracted from the emissions from the grid to give the total GHG savings from installing conduit hydropower. The savings in terms of the social cost of carbon were calculated in the same way as they were for solar power.

Microhydropower

Microhydropower generation potentials were calculated separately for each of the 5 sites designated in the FERC drawings found in Appendix B. In cases where there is not a FERC map already drawn, head would have to be measured at each site. The microhydropower capacity was determined using the following formula:

$$generation\ capacity = head * turbine\ efficiency * water\ density * gravity * discharge$$

[52] for each location based on the head in the FERC drawing. Water density was found using the USGS water density table [122] and the average temperature for Lewiston, Maine [123]. Discharge was based on communications with the Lewiston government – for non-canal scenarios, discharge would have to be measured at each MHP location. This capacity was multiplied by 365 days, 24 hours per day, and .51, because the average hydropower turbine's total generation is about half of its total capacity, to estimate the total potential generation.

Turbine cost was calculated using the following equation:

$$cost = 139318.161 * head^{0.02156} + 0.06372 * discharge^{1.45636} + 155227.37 * projected\ capacity^{0.11053} - 302038.27$$

[59]. This was repeated for each turbine and the individual turbine costs were combined to find the total cost of the MHP network.

GHG emissions and the social cost of carbon were calculated in the same way as for conduit hydropower. These calculations were repeated entirely for the scenario with increased head.

Heating

The total number of electric heaters required was found by determining how many heat pumps or resistance heaters would be necessary for the average residence by type. Houses, apartments in small buildings, apartments in large buildings, and mobile homes were considered. The numbers of these residences in Lewiston was provided by the American Community Survey [12], and the number of heaters required per residence type was provided by Revision Energy [79]. The heaters required will differ based on the climate of the area and the average construction and insulation quality of the buildings. The numbers of heaters per residence, given in Table 16, were multiplied by the number of residences in that category to give total number of heat pumps required by housing category. These numbers were then added to give the total number of each type of heater required by the city.

Electrical demand from the heat pumps and resistance heaters was calculated by multiplying estimates of yearly energy use by heater type, from Revision [79], by the number of heaters of that type. Total yearly demand is a sum of those two numbers.

The price of electricity used was calculated by multiplying the total electricity use by the grid electricity price. Installation price was calculated by multiplying estimated installation prices, given by Revision [79], by the total number of heaters in each category. The total installation cost after rebates from Efficiency Maine was calculated by subtracting $750 from the installation cost for each house, because they are each estimated to have 2 ASHPs, and $500 from each residence type that has only 1 heat pump [80]. These numbers were then added to the unchanged number for mobile homes, as they were assumed to have no heat pumps, to give the total cost after the rebate.

Lifecycle carbon footprint of ASHP was calculated by averaging the values found by one study for ASHPs installed in the types of houses included in the previous calculations [15]. Based on the study, 15% of an ASHP's lifecycle carbon footprint was assumed to represent the footprint of a resistance heater. These numbers were multiplied by the total electricity consumed in one year to estimate the total GHGs produced by the heaters. Like solar, electric heating can completely replace fossil fuel heating, so the emissions from the heaters were subtracted from Lewiston's total emissions from heating to give the total GHG emissions saved by switching to electric heating. The social cost of carbon was calculated in the same way as all of the past technologies.

Conclusion Calculations

The summary numbers found in the conclusion are all derived from the calculations detailed above. The current total potential generation is found by adding the solar potential generation with all improvements, the CHP potential generation with existing turbines, the MHP potential generation at current discharge in the canals and then subtracting the electricity consumed by electric heating. The improved total includes the next-gen CHP turbine potential generation and the MHP generation at the full discharge allotted to the city. The tax credits are done in a similar way; technologies that can receive tax credits are included in one calculation without the credits and in one with them already applied.