A SPATIAL ANALYTIC METHOD FOR THE PRELIMINARY DESIGN OF A DISTRICT ENERGY NETWORK UTILIZING WASTE HEAT IN MIXED-USE JURISDICTIONS

by

Dave Ronn

Submitted in partial fulfilment of the requirements
for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
April 2011

DALHOUSIE UNIVERSITY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “A SPATIAL ANALYTIC METHOD FOR THE PRELIMINARY DESIGN OF A DISTRICT ENERGY NETWORK UTILIZING WASTE HEAT IN MIXED-USE JURISDICTIONS” by Dave Ronn in partial fulfillment of the requirements for the degree of Master of Applied Science.

Dated: April 25, 2011

Supervisor: ___________________________________

Readers: ___________________________________

____

____

DALHOUSIE UNIVERSITY

DATE: April 25, 2011

AUTHOR: Dave Ronn

TITLE: A Spatial Analytic Method for the Preliminary Design of a District Energy Network Utilizing Waste Heat in Mixed-Use Jurisdictions

DEPARTMENT OR SCHOOL: Department of Electrical and Computer Engineering

DEGREE: MASc CONVOCATION: October YEAR: 2011

____

Signature of Author

TABLE OF CONTENTS

LIST OF TABLES vi
LIST OF FIGURES vii
ABSTRACT viii
LIST OF ABBREVIATIONS AND SYMBOLS USED ix
ACKNOWLEDGEMENTS x
CHAPTER 1 : INTRODUCTION 1
  1.1 Cities and Energy Use 2
    1.1.1 Energy Security 3
    1.1.2 Climate Change 5
  1.2 Thesis Objectives 7
  1.3 Thesis Organization 8
CHAPTER 2 : BACKGROUND 9
  2.1 Energy and Urban Planning 9
  2.2 Mixed-Use Planning 11
  2.3 Cities and Waste Heat 14
  2.4 District Energy Systems 17
    2.4.1 System Overview 18
    2.4.2 DHS and Waste Heat 20
    2.4.3 Heat Exchange Technology 23
    2.4.4 Waste Heat Production 24
    2.4.5 Cross-Optimization 27
  2.5 Thermal Storage 31
  2.6 Buildings of a Mixed-Use Jurisdiction 33
    2.6.1 Building Loads Estimation 34
    2.6.2 DHS Interconnections 36
  2.7 Summary 37
CHAPTER 3 : DESIGN AND METHOD 38
  3.1 Method Overview 38
  3.2 Phase 1: Identification Component 41

3.2.1 Sink Cluster SH and DHW Load Profiles (Spatial Layer) 42
3.2.2 Industrial and Commercial Heat Load Profiles (Spatial Layer) 45
3.2.3 Cluster Analysis (Hub Layer) 49
3.3 Phase 2: Preliminary Design (Nodes Layer) 50
3.3.1 Establishing the Network 52
3.3.2 Nodes_1 55
3.3.3 Nodes_2 57
3.3.4 Distribution Network 59
3.4 Fuel Savings and GHG Emissions 67
3.5 Discussion on Calculations 68
3.6 Summary 68
CHAPTER 4 : IMPLEMENTATION AND RESULTS 69
4.1 Implementation 69
4.2 Case Study 74
4.2.1 Overview 75
4.2.2 Phase I : Spatial Layer 76
4.2.3 Hub Layer 80
4.2.4 Phase II : Nodes Layer 84
4.2.5 DHS Network Sizing 86
4.2.6 DHS Network Design Formulation 88
4.2.7 Fuel and GHG Savings 91
4.3 DHS Network and Energy Security 92
4.4 Summary 93
CHAPTER 5 : CONCLUSIONS 94
5.1 Future Work 97
APPENDIX 1 99
APPENDIX 2 105
APPENDIX 3 106
APPENDIX 4 107
BIBLIOGRAPHY 110

LIST OF TABLES

Table 1. Five-points of consideration for community energy planning 13
Table 2. Industrial, commercial, institutional sources and applications of waste heat 21
Table 3. Building types and activities served in a DHS network 42
Table 4. Examples and characteristics of comm. and ind. processes in mixed-use jurisdictions 49
Table 5. Data inputs for network optimization weights 54
Table 6. Peak demand improvement factors from 56
Table 7. Technological limitations of Rankine-driven heat pump using waste stream heat 59
Table 8. Assumptions of Implementation and Case Study 74
Table 9. Hypothetical supply loads of hubs for jurisdiction 78
Table 10. Building loads according to storeys and vintage 79
Table 11. Indices of building heating loads of jurisdiction 82
Table 12. Network optimization for DHS case study 89
Table 13. GHG emissions for primary heating fuels used in jurisdiction 91
Table 14. Fuel savings and GHG emissions for jurisdiction 91
Table 15. Heat Recovery Technologies and Parameters 103

LIST OF FIGURES

Figure 1. Basic context diagram of an energy supply system 4
Figure 2. Schematic depiction of thermal energy in urban area 15
Figure 3. Urban regions and energy opportunities 24
Figure 4. System diagram of the district heating system 22
Figure 5. Commercial laundromat energy flow from propane to hot air exhaust 26
Figure 6. Entropy of source (supply) and end-use (process) in the urban environment 29
Figure 7. Typical urban energy system versus a waste-heat optimizing energy system 31
Figure 8. Energy intensity for Canadian households by dwelling 35
Figure 9. DHS context diagram 38
Figure 10. A graphical representation of the two phases 40
Figure 11. Methodology for developing heat sink clusters 43
Figure 12. Hypothetical DHS mapping to optimize select targets 51
Figure 13. Relationship between primary and secondary system of DHS 61
Figure 14. DHS network with one source and multiple sinks 61
Figure 15. Single-commodity network with multiple sources, multiple sinks, and transshipment node 65
Figure 16. Map of North End Halifax 75
Figure 17. Thermal map for Halifax peninsula 77
Figure 18. Household types by tract in jurisdiction 80
Figure 19. Cluster analysis for high-density residential heat sinks 81
Figure 20. Load duration curve for heat sink clusters of jurisdiction 83
Figure 21. Network and shortest distances measured for arc routes 85
Figure 22. Network diagram of connectivity and potential flows for DHS 87
Figure 23. Optimized DHS network for jurisdiction 90

ABSTRACT

A city's characteristics of mixed-use zoning, diverse built form, high-density development, and residual heat generation by urban processes, present potential for optimizing the thermal energy end-use of certain waste streams.

A method was developed to identify sources of waste thermal energy and heat demand clusters in a mixed-use jurisdiction and design a preliminary primary network of a district heating system based on these waste heat sources.

The method applies systems analysis, energy potential mapping (GIS spatial analysis) and network optimization (linear programming) techniques. The method is implemented using a case study of data for peninsular Halifax.

Finally, the method and implementation's influence on climate change (i.e. a reduction in GHG emissions) and energy security, two central themes of this research, are discussed.

LIST OF ABBREVIATIONS AND SYMBOLS USED

CHP : Combined heat and power

CH_4 : Methane

CO_2 : Carbon dioxide

CO_2e: Carbon dioxide equivalent

DES : District energy system

DHS : District heating system

DHW : Domestic hot water

GHG : Greenhouse gas(es)

GIS : Geographic information system

LFO : Light fuel oil

LP: Linear programming

MW_e : Megawatt electrical

N_2O : Nitrous oxide

SH : Space heating

ACKNOWLEDGEMENTS

I would like to, firstly, express tremendous gratitude to my thesis supervisor, Dr. Larry Hughes, for his guidance, feedback, and support throughout the course of this thesis and my degree.

My appreciation also goes to the Energy Research Group, including members Shanmuga Sundaram, Hari Lakshminarayanan, Nikhil Chaudhry, Vinay Chatharaju and Mark Gardner.

Thanks are also due to my thesis committee members, Dr. Timothy Little and Professor Steven Mannell for their extremely useful comments during the research of this thesis.

My gratitude also goes to Dr. Alain Joseph at the NSCC, for providing constructive suggestions and important considerations at each step along the way.

I would also like to thank Dr. Lukas Swan and Dr. Peter Allen in the Department of Mechanical Engineering at Dalhousie University for providing data and direction on household energy use profiles.

I am grateful to Raymond Jahncke at the GIS Centre and Dr. Maria Vasardani for their critical role in elucidating concepts related to use of the spatial software.

I extend my appreciation to Michael Steeleworthy and Phyllis Ross, at Data Information Services of Dalhousie Libraries, for their assistance in clarifying the nuances of data acquisition.

Finally, a heartfelt expression of gratitude and indebtedness goes to my partner, Angela, for her patience, encouragement, and unwavering support as I completed this thesis.

CHAPTER 1 : INTRODUCTION

City systems typically extract energy for large-scale consumption from their host environments, local or global, only to discharge the low-entropy waste back to the same environment or their direct surroundings. Thermodynamically, the city itself can be described as a dissipative process akin to parasitism (Rees 2003). The ecological, social and financial costs associated with energy flows between the city and its environment call into question the state of the system's energy security.

Energy security, the uninterrupted physical availability at a price which is affordable, while respecting environment concerns (IEA 2010), can be improved by a range of measures including those that reduce consumption of non-secure sources, replace them with or restrict them to more secure sources, or both (L. Hughes 2009).

In urban planning, developing densely populated spaces with multiple uses can further reduce a jurisdiction's energy use by optimizing energy flows (Grant 2004). A complimentary approach for energy replacement can be to utilize waste streams for the micro-generation of electricity or the extraction of heat to accommodate some of the energy needs of the jurisdiction (Haidar and Ghojel 2002).

While individual buildings improve their energy performance or district heating schemes emerge between a few customers and the energy supplier, it is becoming increasingly important to approach thermal energy systems holistically in city planning (Ward and Mohammed 2009).

Given the diverse built form of many cities, energy-intensive processes and high-density development, cities can hold countless opportunities to match heating demands with proximate commercial or industrial sources of low-to-medium temperature waste streams (Broersma and Dobbelsteen 2008). However, optimizing the different relationships that can exist between energy sources and end uses requires a careful analysis of energy mix parameters.

Energy potential mapping considers the jurisdiction as a network of energy and material flows, considering local exergetic and energy potentials for sustainable regional planning (Dobbelsteen, et al. 2007) and improving energy security.

Applying systems analysis techniques to urban energy planning can assist in identifying multiple sources and sinks, while designing energy systems that can balance energy loads with demands. Recovering the losses of an energy system for further use as sources in a jurisdiction's energy systems, as is the focus of this research, can maximize the potential of the energy supply to that jurisdiction.

By integrating storage systems, as energy reservoirs to match load with demand, and upgrading or converting the energy to a more useable state, waste streams can be assessed for exploitation while minimizing costs to the jurisdiction.

The supply in a network can be measured both in terms of energy or exergy, the latter describing a measure of useful work potential of available energy.

Thermal energy from waste heat sources in a mixed-use jurisdiction environment can include heat-generating facilities such as kilns for pottery and ceramics, bakery ovens, laundromat washers and dryers, coffee roasters, ovens in commercial kitchens, small to medium-sized breweries, data centers and telecommunication systems.

1.1 Cities and Energy Use

Today, humanity faces a critical turning point in the history of the planet. Carbon dioxide emissions produced through the burning of fossil fuels for electrical generation, heat and transportation have contributed to the climatic phenomenon known as global warming. With already-crowded city conditions –characterized by increased traffic and building sprawl- facing the pressure of the world's ever-growing population, climatic events impose a further stress on the urban edifice.

This, coupled with a mounting dependence on imported fuels, more petroleum-consuming vehicles on the road, rising energy costs, an economic downturn and an ever-increasing metropolitan influx, have led to constrains on energy supply, often to the detriment of the city's energy security.

Paradoxically, there exists great hope in the cities of tomorrow. Residents of metropolitan areas in the United States, for example, are found to have smaller carbon footprints than the average American (Brown and Sarzynski 2008). Cities, given their high-density layout, also possess opportunities for energy reduction via communal resources (e.g. public transit) and structural form (e.g. shared partitions in apartment building envelopes).

Similarly, cities can establish fixed urban growth boundaries, revitalize old districts to provide incentives against urban flight, plan road infrastructure to encourage more sustainable transportation, and provide the necessary capital to stimulate energy projects that are more secure and ecologically sound.

1.1.1 Energy Security

Energy security is becoming an issue of paramount importance in many jurisdictions. With geopolitical conflicts over resources, volatile global energy markets, increased costs of production, and a disproportionate cultural reliance on finite (fossil fuel-based) energy sources, there is strong impetus to re-assess our energy systems.

It is assumed that cities will continue to grow in an energy-supply restricted environment. At a localized level, a community can either reduce their energy demand, or energy systems can have diversified supply or infrastructure (L. Hughes 2009). The dependability of infrastructure, generally, is of major concern as there continues to be cases of vulnerable energy 'carriers'.

As illustrated in Figure 1, a jurisdiction can also influence an energy supply system before it reaches the end-user (i.e. consumer) depending on said jurisdiction's priorities; be they environmental, economic, or social.

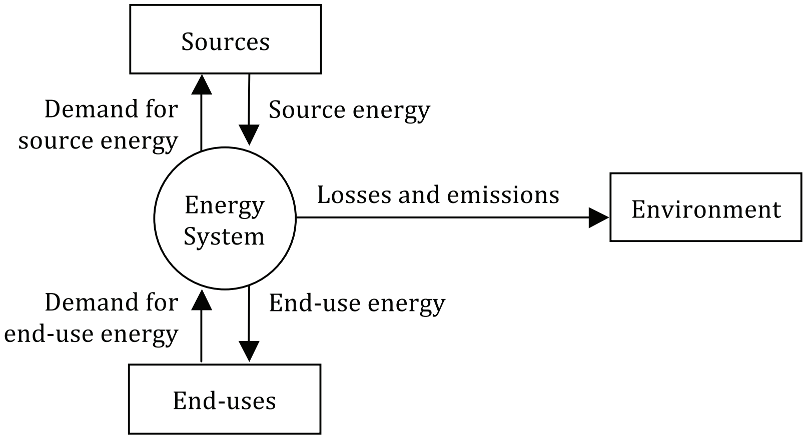


Figure 1. Basic context diagram of an energy supply system (Hughes 2011)

Some of the losses to the environment can be recovered and used as potential sources to the energy system. As will be described, the type of losses relevant to this research is thermal energy from process streams of industrial facilities.

A set of conditions that can be used to map out a jurisdiction's energy security is the four 'A's approach developed by the Asia-Pacific Energy Research Center (APERC). The four 'A's are availability, accessibility, affordability, and acceptability (APERC 2007) and provide a useful framework to analyze a jurisdiction's energy security and, subsequently, shape policy and practice to improve its standing.

A complementary set of actions that can be taken, known as the four 'R's, consists of recommended categories of consideration when assessing energy systems.

The first 'R' is *review*, and refers to understanding the problem, and reviewing existing as well as potential sources, systems and services of the jurisdiction; the second 'R' represents those steps that *reduce* energy demand, either via energy conservation or efficiency measures and technologies, or both; the third 'R', refers to strategies that *replace* energy supplies or infrastructure for alternative energy sources; the fourth 'R', relates to measures that *restrict* any new demand to sources deemed secure by the jurisdiction (L. Hughes 2007).

In the case of the urban setting, consideration may be given to a myriad of region-specific issues. These may include municipal environmental declarations; legislative environmental acts; socio-cultural implications; local customs; emerging community clusters; revitalization schemes; preservation of historic sites; green spaces; matters of governance; and mixed-income neighborhoods. Ideally, energy policy and planning for the urban environment complements the jurisdiction's objectives in these other domains.

1.1.2 Climate Change

Climate change can be defined as a change in the planet's climate as a direct or indirect result of anthropogenic activities that alter the composition of the atmosphere and beyond the natural climatic variability recorded over similar time periods (UN 1992). The primary cause-and-effect relationship of concern is understood to be the emission of greenhouse gases and the resultant warming of the globe, respectively; this leads to weather patterns, both chronic and acute, that are untenable for both human existence as well as that of other species.

Carbon dioxide (CO_2), a byproduct emitted by combusting fossil fuels, is the primary human-produced greenhouse gas affecting the planet's radiative balance (IPCC 2002). As such, jurisdictions globally have made varying degrees of commitment to curbing the carbon dioxide emitted.

Cities are particularly at risk of extreme weather events, as opposed to gradual shifts, catalyzed by climate change given the proximity and locating of cities in or near "coastal areas, ravines, and other risk-prone regions" (UN-Habitat 2009). Given a city's condensed populations and dense building layouts, climate-related extreme events can jeopardize resource infrastructure generally and energy systems specifically. These urban "lifelines" as they are known (McBean and Henstra 2003), represent centralized carriers –combined sewers, electrical grids, and telecommunication networks- that while seemingly practical in a heavily populated area, are open to vulnerabilities.

Energy use is the largest source of greenhouse gas emissions, representing approximately 65% of global emissions (IEA 2009). By examining ways to reduce energy consumption and reassess the energy supplies used, a jurisdiction can consequently identify ways to cut its emissions and curb polluting practices.

Typically, programs and technologies to address climate change fall into either one of two strategies: mitigation or adaptation. Mitigation involves those activities or apparatuses that reduce greenhouse gas (GHG) emissions as a means to curb the pace of climate change and include promoting energy conservation and efficiency. In cities, this typically means developing renewable energy projects; limiting sprawl; and supporting public transportation (Ligeti and Wieditz 2007).

Adaptation, conversely, accounts for the impending effects of climate change and includes steps to limit a jurisdiction's vulnerability, whether preemptively –as in 'anticipatory adaptation'- or to deal with a climate-change related as, or after, its already happened (Smit, et al. 2000). Examples for such energy measures in cities are varied based on the local climate, but may include establishing "comfort shelters" during cold snaps and having petroleum reserves for home heating (Hughes and Ron, Energy security in the residential sector: rapid responses to heating emergencies 2009).

Distributed energy systems (Ligeti and Wieditz 2007) and waste heat recovery have the potential to be both *adaptive* and *mitigating* climate change strategies in a city.

The decentralization of energy systems can reduce a jurisdiction's vulnerability to extreme climatic events by diversifying its lifelines.

1.2 Thesis Objectives

The objective of this thesis is to develop a method to identify sources of waste thermal energy and sinks of heat demand in a mixed-use jurisdiction. With this information, the method creates a preliminary shortest-path network for a district energy system (DES). The resulting network is then assessed based on its potential to reduce greenhouse gas emissions and improve energy security.

The method will minimize the system's cost and greenhouse gas emissions by capturing residual thermal energy for "clusters" of thermal sources and sinks. Once the locations and measurements of waste heat are known, the method will develop the energy end-use sequence and network routing, incorporating heat up-graders, stores, or both.

The method is intended as a screening and predictive assessment of establishing a waste heat-based district energy system in a jurisdiction. It is intended as a tool for planners, architects, and engineers retrofitting, integrating, or planning new buildings in mixed-use jurisdictions.

The novelty of the method proposed by this research is its approach to holistically identifying waste heat sources and sink potentials in a jurisdiction; developing a preliminary design of a district heating system network's routing based on minimization of cost; producing a spatial representation for planning purposes; and examining a single commodity system, being waste heat.

1.3 Thesis Organization

The next chapter provides a literature review to contextualize district energy, waste heat utilization, and urban energy planning. This section then expands on such energy systems discussing low-exergy flows, waste heat recovery technologies and storage options for building clusters in a mixed-use setting.

Chapter three describes the design of the method and implementation of it. The method's design and theoretical underpinning is discussed, while a number of different implementations are considered and the limitations of each are explained.

The fourth chapter presents a case study to simulate the tool with actual datasets for an actual high-density mixed-use jurisdiction. The results and assumptions are discussed.

Chapter five summarizes the research, and includes concluding remarks as well as recommendations. Considerations for future work to further this research are also touched upon.

CHAPTER 2 : BACKGROUND

> Lively, diverse, intense cities contain the seeds of their own regeneration, with energy enough to carry over for problems and needs outside themselves.
>
> – Jane Jacobs

With oil reserves in decline, energy security compromised, an impending economic downturn, and concern over climate change from human-made greenhouse gases, questions around reducing energy consumption —as well as replacing supply and infrastructure- are of critical importance. Many of the answers may lie in the urban milieu.

Urban planning, generally, is defined as the technical and social study, as well as management, of land use, building, communication and transportation infrastructure (Levent 2008) to effect plans, policies, and protocols that advance the built, economic, natural and social environment of urban populations.

2.1 Energy and Urban Planning

As the global population continues to grow and people are pulled into cities for mostly economic reasons (Yap 2002), humanity is faced with the ever-increasing need to ensure adequate resource management. The continued influx of people has, in-turn, created a tension-release type effect between cities and the centralized industries that supply their demand. Indeed, the rise of the metropolitan entity to serve mostly commercial interests has induced a limitless growth model upon a finite area (GA 1997).

To exemplify this trend, whereas at the start of the 20th century, one out of every two Canadians lived in urban centres, today four out of five Canadians call a city their home. Nearly ninety percent of the growth in Canada's total population has taken place in metropolitan areas and, between 2001 and 2006, the population living in urban areas increased by 11% and continues to grow (StatsCan, Census snapshot of Canada - Urbanization 2008).

High-density development is also a sustainable means to conserve land and resources, when done in accordance with sustainable development frameworks such as the Adaptation Strategies for Climate Change in the Urban Environment, ASSCUE, developed in the UK (CURE 2003) and applied in Great Manchester; or Factor-2 community energy planning in North America (NRCan 2007), such as that undertaken in the City of Victoria.

While new housing developments, eco-towns, and isolated zero-carbon communities attract more attention in a culture increasingly accounting for concerns over climate change (Weizsäcker, Lovins and Lovins 1997) and energy security, these are no 'silver bullet' solution. Also, when taking a life cycle analysis, eco-towns have faired poorly considering transportation-related energy and cost of resource inputs given their relative isolation (Owen 2009).

Energy use affects all aspects of urban life, from how people get to work to the cultural spaces citizens enjoy; all rely on a comprehensive energy network that may be disjointed or connected; rigid or flexible (Bose 2010).

One extremely common fixture in the discourse surrounding energy use and urban planning is that which relates to transportation infrastructure. Such planning can result in a range of desired outcomes through physical developments of a city's layout. These may include safety measures being implemented, decongesting traffic flows, reducing route driving time, or mitigating greenhouse gas emissions and urban smog through sustainable transportation schemes (e.g. bicycle lanes, electric trains).

Power generation, as well as space heating and cooling in the urban environment can be often overlooked in the continued planning of a city's development. Of course, individual buildings may have advanced heating options, R-values, and non-hydrocarbon-based electrical generation. But, given the voluntary nature of most green building codes and lack of short-term financial incentives to warrant the capital expenditure, this remains a fate largely contingent upon the ideological persuasions of the property owner.

City blocks and the tenants that inhabit them, whether they are residential or commercial, do not emerge overnight; a neighborhood is a dynamic, ever-evolving, ebbing-and-flowing phenomenon. However, the ways in which cities grow are in large part governed by zoning laws, builder interests, and local customs.

2.2 Mixed-Use Planning

Within any city, mixed-use developments, zones, or jurisdictions are defined as those that accommodate multiple types of uses (i.e. residential, commercial, office, industrial, etc). With regards to the focus of this research, mixed-use jurisdictions refer to those that house any combination of commercial, residential, institutional, or light industrial developments.

Mixed-use developments or zones are a common trend in many jurisdictions with high urban density. As can still be seen in many European countries, the mixed-used pattern of urban development was negatively impacted by the industrialization period which opted for a centralization and isolation of building types creating distinct single-use boundaries around power production, manufacturing, and residential units (Goupil 2008). Legislating single-use zoning eventually gave way to the phenomenon known as urban sprawl and the inception of the suburban neighborhood, whereby land-use had a low density.

Furthermore, high-density land development with mixed-use can have the benefits of reducing transportation by localizing opportunities for business, employment, and leisurely activities.

In urban planning, developing spaces that densely populate a jurisdiction with differing uses can further reduce energy use by linking potential energy supply, possibly considered a waste stream or energy loss at one site, with requirements for energy supply at another site. A complimentary approach for energy replacement can be to employ on-site thermal waste streams towards some of the thermal energy needs of a jurisdiction.

There are three distinct types of mixed use planning: intensifying one particular land categorization, diversifying the uses, or integrating previously separate land categorizations into a common jurisdiction (Grant 2004). As with the third type, establishing industrial operations in residential areas or including apartment units above commercial storefronts is beginning to be a common feature of cities as land use shifts to make way for increasing populations, neighborhoods accommodate varying income brackets, and economic 'hubs' spatially morph (Ward and Mohammed 2009).

Smart growth, an urban planning theory centered on "finding physical and policy solutions to improve the outcomes of growth" (Grant 2004), promotes mixed-use planning as a means to enhance both economic self-sufficiency and social diversity. As its primary tenets, apart from mixed-use planning, smart growth advocates compact building design; neighbourhood layouts conducive to walking; diverse choices in modes of transportation and types of housing; the conservation of open and green spaces; as well as networking or collaborations among various communities or stakeholders, or both, of the jurisdiction (Smart Growth Network 2004). In its implementation as policy, smart growth "takes an incentive-based rather than a regulatory approach to reversing trends" (Frece 2001).

A successor to the environmentally-oriented sustainable development movement and the socially-focused healthy cities movements in urban planning, smart growth continues their legacy of prioritizing "bottom-up" solutions (Grant 2004). Where it differs is in its challenge of not whether cities grow at all but, instead, *how* they grow and bettering the products of this growth.

The mixed-use city generally provides a multitude of energy system possibilities given its diverse built form, energy-intensive processes and high-density construction. Determining the links between sources and sinks for preliminary design of an energy system, such as a DES, requires a consideration of supply-mix parameters as described below.

To improve energy security and reduce CO_2 emissions in cities, a set of inter-related energy management criteria can be applied to guide and assess the feasibility of strategies being reviewed. The supply mix parameters and general criteria are thematically inter-related.

Applying such a systematic approach to energy planning for the urban environment, as shown in Table 1, can produce innovative ways of managing energy resources; not just by allowing for flexibility through decentralization but also by encouraging cross-optimization through co-dependence.

Table 1. Five-points of consideration for community energy planning (Dodd 2008)

No.	Supply mix parameters	General criteria
1	Technology	Benefits of low-carbon energy conversion and generation tech.
2	Location	Access to renewable and waste resources in local environment
3	Consumers	Forms and grades of energy required for different end-uses
4	Delivery mechanism	Parameters for cost effective and efficient deployment
5	Scale	Scale and form of development opportunities

Typically, the exclusion of comprehensive energy assessments in urban planning results in high-quality energy being applied to low-temperature applications; for example, electricity or oil used for space heating. By considering the quality and quantity of the energy supply and secondary energy options in mixed-use settings, planning processes can better match demand and supply for a given jurisdiction.

As such, an assessment tool is necessary to measure the potential and efficiency of residual thermal energy for heating (and power generation) infrastructure in mixed-use developments.

2.3 Cities and Waste Heat

Cities, in accordance with the second law of thermodynamics, can be thought of as dissipative organisms, given their practice of consuming energy for development while "increasing disorder at higher levels in the systems hierarchy" (Schneider and Kay 1992). By extension, the survival of cities as a whole is limited by the thermodynamic load-bearing capacity of the "host environment", the ecosphere from which they draw (Rees and Wackernagel 1996).

There are numerous sources and qualities of waste heat in the urban environment from the warm grey-water of a residential dishwasher to the hot air discharged from a commercial bakery. Understanding and quantifying their availability is the first step towards optimizing their use in the urban environment.

Sensible heat is thermal energy associated with a change in temperature, the amount of which is a function of both the temperature differential, the phase, as well as characteristics (volume, quantity, specific heat) of the waste stream media. Recovering sensible heat from waste streams involves heat transfer by radiation, conduction or convection (EMR 1985).

It has been observed that in the US, anthropogenic heat production in cities can vary from between 0.08 to 2.30 kWh/m^2/day depending on everything from urban activities to transportation infrastructure (Sass 2009).

Numerous commercial processes, centered around urban areas, generate various classes of waste heat (see Table 2) that is otherwise dissipated and lost to the surrounding air. Coupled with such processes, HVAC (heat, ventilation and air-conditioning), artificial lighting and appliances are the primary contributors to the heat loss via building envelopes and air exchanger units.

The urban micro-climate is characterized by this excess heat production, airflow and humidity air pollution, and the built environment (Yannas 2001).

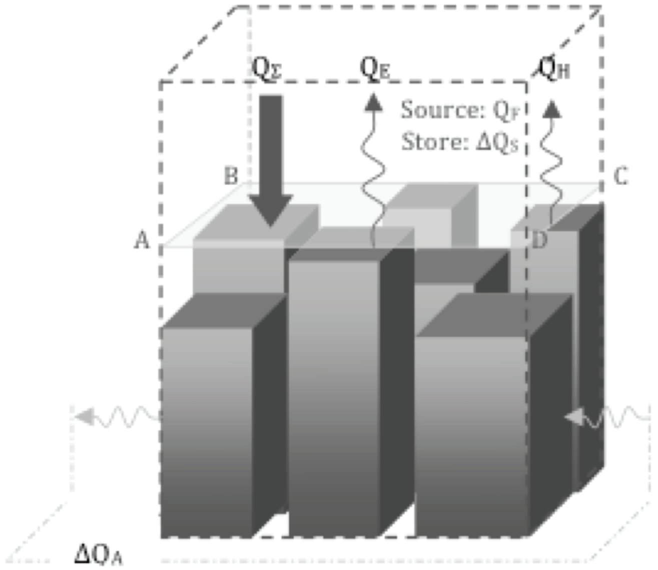


Figure 2. Schematic depiction of thermal energy in urban area (Oke 1988)

As shown in Figure 2, the heat of a city can be measured based on equation 1 (Oke 1988), which describes the surface energy budget.

$$Q_\Sigma + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \tag{1}$$

Where Q_Σ is the net of all wave radiation; Q_F is the combustion-related heat release; Q_H and Q_E are the turbulent sensible and latent heat flux density, respectively; and ΔQ_S + ΔQ_A represent the net heat of storage and advection, respectively.

The net of all wave radiation refers to the solar radiation that is either short-wave and direct, much of which is reflected back from the earth's surface, or long-wave which heats up in the earth's atmosphere before being re-directed to the surface (Emmanuel 2005). The turbulent heat flux densities relate to energy heating the air or water of, and subsequently convected from, the urban system. The net heat of storage is also known as the subsurface heat flux (Oke 1988), which is in direct proportion to the thermal conductivity of building materials in the urban environment.

The cumulative outcome of an unfettered supply of thermal energy discharge is the increased temperature of the jurisdiction in a process known as the *urban heat-island effect* (Emmanuel 2005). Such heat can, as in the case of parts of Europe, surpass that which is available by solar radiation (Yannas 2001).

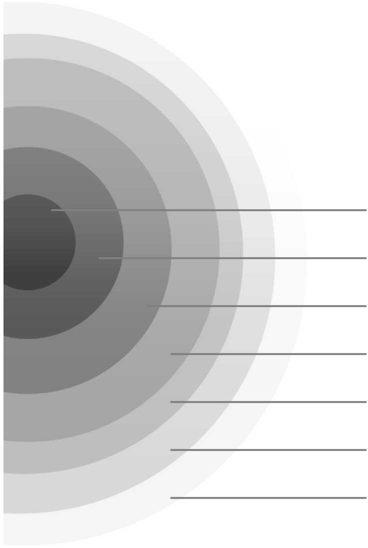
The main causes of such a temperature rise include the release and refection of heat from activities and processes listed in the equation above; incidental thermal absorption by building materials such as concrete and brick; the emission of hygroscopic pollutants by transportation and industry contributing to the development of low-lying clouds, smog and pollution domes (Smith 2010). Common mitigation strategies typically include improving building insulation, and integrating green areas or artificial water bodies to capitalize on evapotranspiration and evaporative cooling (Dobbelsteen, Dorst and Timmeren 2009).

It remains difficult to predict the precise contribution the urban heat island effect has on overall temperatures (CCME 2003). In Ottawa, a climate characteristic of many other Canadian cities, the urban heat island effect has gradually increased the temperature at a rate of >0.01°C yr^{-1} in the last 100 years, while no such warming is apparent in the surrounding rural zones (Prokoph 2008). Presumably, capturing some of that residual heat could apply it to practical uses.

With new building construction, there are a number of preventative measures to limit the amount of thermal energy that escapes into the atmosphere. This includes accounting for structural orientation, shading features, morphology, envelope insulation, and selecting building materials that are cool, reflective or have higher efficiencies (Smith 2010). The built environment must also integrate natural landscapes, such as water bodies and green zones, within high-density areas.

These are, of course, a first measure for consideration in energy conservation and efficiency that can help, in turn, mitigate the urban heat island effect as well as GHG emissions. The systems therein, however, are equally important.

As illustrated in Figure 3, the city can be subdivided by urban areas or 'archetypes', which adhere to specific built forms and have implicit energy opportunities worthy of being explored and potentially exploited.



Urban areas	Energy opportunities
City centre	Mixed-use layout provides possibilities for CHP, waste heat recovery, and cross-optimization
Edge of centre	Heat density of institutions supplemented by RE
Inner city districts	Selective remodeling/improvement of buildings
Industrial estates	Ideal to locate large energy projects (ex. biomass)
Suburban districts	Ideal for small microgeneration projects
Urban extensions	Base planning on low-carbon community energy
Rural hinterlands	Medium to large-scale generation; farm relations

Figure 3. Urban regions and energy opportunities (Dodd 2008)

Within these regional archetypes are energy profiles for average households or building types within the neighborhood. These include consumption patterns for space heating, hot water, and electricity (used in lighting and appliances). The effect of "urban design, neighborhood location and lifestyle variables on associated energy consumption" (NRCan 2009) can also be included to define a building type.

2.4 District Energy Systems

District energy systems (DES) can be defined as a means to transfer thermal energy from source to sink, or from supplier to consumer (Gilmour and Warren 2008). The media transferring this energy can be hot water, steam, chilled water, or a combination thereof. In creating a unified network from otherwise detached sources and sinks, a DES provides integrated control of thermal loads for a jurisdiction.

2.4.1 System Overview

The three main sub-systems of a DES can be explained using the energy system context diagram illustrated in Figure 1. These sub-systems are the collection or production of thermal energy, with or without power generation (i.e. combined heat and power, CHP); the distribution network from the thermal energy sources to the end-users, otherwise known as the primary network; and the transfer of thermal energy to the building sinks, also referred to as the secondary network (Arkay and Blais 1996). Once thermal energy is extracted by the secondary network return pipes send the heating medium back to the sources for heating again.

The advantages of district energy systems over conventional decentralized forms of thermal energy production for non-industrial uses include their efficiency, flexibility and environmental benefits. The efficiency of a DES is a function of the amount of fuel saved from displacing conventional means; electric heaters, for example, are deriving electricity from power plants typically operating at efficiencies of 30 to 45% (Gilmour and Warren 2008).

Environmentally, the displaced fuel and higher efficiencies result in fewer GHG emissions associated with a DES. Another environmental benefit to a DES, when matched with a CHP plant, is that the point of combustion is normally sited far from the final point of use (Diamant and Kut 1981) to mitigate respiratory irritants. Also, a DES offers increased fuel flexibility by diversifying its sources; this can improve a jurisdiction's energy security (Dincer and Rosen 2007).

DES's are configured in one of two layouts, being either radial or looped (Orlando 1997). In a radial network configuration, thermal energy is supplied to the end-user demand through single-path pipelines, while in the looped, there are multiple paths to deliver the heat from source to sink. Although looped systems have higher capital costs, their grid configuration ensures system reliability and decreased maintenance costs over the lifespan of the DES (Arkay and Blais 1996).

These network configurations can correspond to city district layouts. Radial, or "hub-and-spoke", systems have streets branching out from a single location and represent fixed routes (APA 2006). Conversely, a city district with a grid layout presents a variety of route scenarios given its configuration of intersecting parallel and perpendicular streets.

The thermal energy of a DES may be applied to space heating (SH), cooling, domestic hot water (DHW), microgeneration, or any combination thereof.

As this particular method aims to develop a preliminary DES hot-water network utilizing industrial waste heat for SH and DHW end-use, the following discussion pertains to a district heating system (DHS) specifically and, from hereon in, will refer to the system as such.

There is potential, as well, for the development of multi-criteria analysis tools for DES planning using waste heat and waste product recovery potential for utilization in the aforementioned applications.

Multi-criteria decision analysis tools are effective within a subjective framework, when allowing decision-makers to qualitatively rank the criteria of a system based on their assigned weights (Saaty 1980). Such tools are useful for ensuring that requirements of all stakeholders for a planned DHS are met.

Consequently, tools with flexibility for diverse scenarios, but built upon a quantitative foundation can complement the multi-criteria decision analytical tools.

2.4.2 DHS and Waste Heat

Typically, district heating systems are designed to use fossil fuels to produce the thermal energy required to meet demands. In Canada, for example, most district heating systems use natural gas as their primary fuel type and Bunker A fuel oil as their secondary fuel type (Gilmour and Warren 2009).

For waste heat to be identified and used as a heating source in a DHS primary network, a number of parameters must be defined. These include the accessibility and containment of the waste heat source; the distance between the source and the demand; the state and quality of the waste heat; the extent to which heating upgrade technology is required; the need for sanitization of the waste heat, contingent on end-use. Assessing these variables will also determine the most suitable waste heat recovery technology, which may include direct usage, heat exchangers, or heat pumps.

By taking an inventory of waste heat availability and heat load requirements for a jurisdiction, a feasibility assessment can be performed to determine whether waste heat processes can be concentrated in a jurisdiction with mixed-use planning to serve heat demands.

The energy content associated with a residual heat source can be calculated with the basic heat transfer calculation described in equation 2 (Caputo, Cardarelli and Pelagagge 1996).

$$E = c_p Q \Delta T \tag{2}$$

Where E is energy (kW); c_p is specific heat capacity [kJ/(kg·°K)] or [kJ/(m^3·K)]; Q is mass flow-rate or volumetric flow-rate (kg/s) or (m^3/s); ΔT is the thermodynamic temperature differential (°K). While sensible heat transfer is the predominant thermal rate in low-exergy systems, the latent heat of vaporization (kJ/kg) can replaced in the above equation to calculate latent heat transfer.

As previously discussed, waste heat recovery from industrial applications can be applied to residential and commercial uses (Lokuch 1980). Waste heat can also be recovered or upgraded with heat exchanger and heat pump technology to serve mixed-use urban areas.

In Table 2, some of the recovery applications associated with processes of various heat classes can provide guidance in the infrastructural development of a jurisdiction's energy systems.

Table 2. Industrial, commercial, institutional sources and applications of waste heat* (EMR 1985)

Heat Class	**Temp. Range (°C)**	**Type of Facility**			**Heat Source**	**Potential End-Use ***				
		Ind.	Comm.	Inst.		PS	PCA	PH	SH	DHW
High-grade	1600-2700 650-1000	■			Electrical refractory furnace exhaust; Waste incinerator exhaust	■	■		■	
Med-grade	375-550 375-500 230-250	■			Gas turbine exhaust; Diesel generator exhaust; Steam boiler exhaust		■		■	
	230-600 150-230 175-230		■		Dry/bake oven exhaust; Dryer exhaust; Furnace flue gas		■			
Low-grade	150-230 85-150 55-95	■			Steam boiler exhaust; Dryer exhaust; Process steam condensate			■	■	
	85-1500 150-230		■		Steam boiler exhaust; Dryer exhaust		■	■	■	
	150-230 175-230			■	Steam boiler exhaust; Furnace flue gas		■		■	■
Very Low-grade	25-50 25-50	■			Air compr. cooling water; Power plant cooling water		■		■	■
	30-45 30-45		■		Air conditioning; Process wastewater				■	■
	30-45			■	Refrigeration and air conditioning				■	■
Other	NA		■		Fryer exhaust; Condenser exhaust; Ventilation exhaust				■	■

---

[*] Note: PS = process steam; PCA = preheat combustion air; PH = process heat; SH = space heat; DHW = domestic hot water

Within a district heating system, waste heat can be distributed to many end-users from a single-point source or collected from many sources and channeled to a single-point destination, or both.

A model for a robust DHS based on waste heat sources has been proposed by Ajah, Patil and Herder and is shown in Figure 4. The model, representing a branched system, is designed to allow for system flexibility, multiple inputs, and maximizing of exergy efficiency in a jurisdiction.

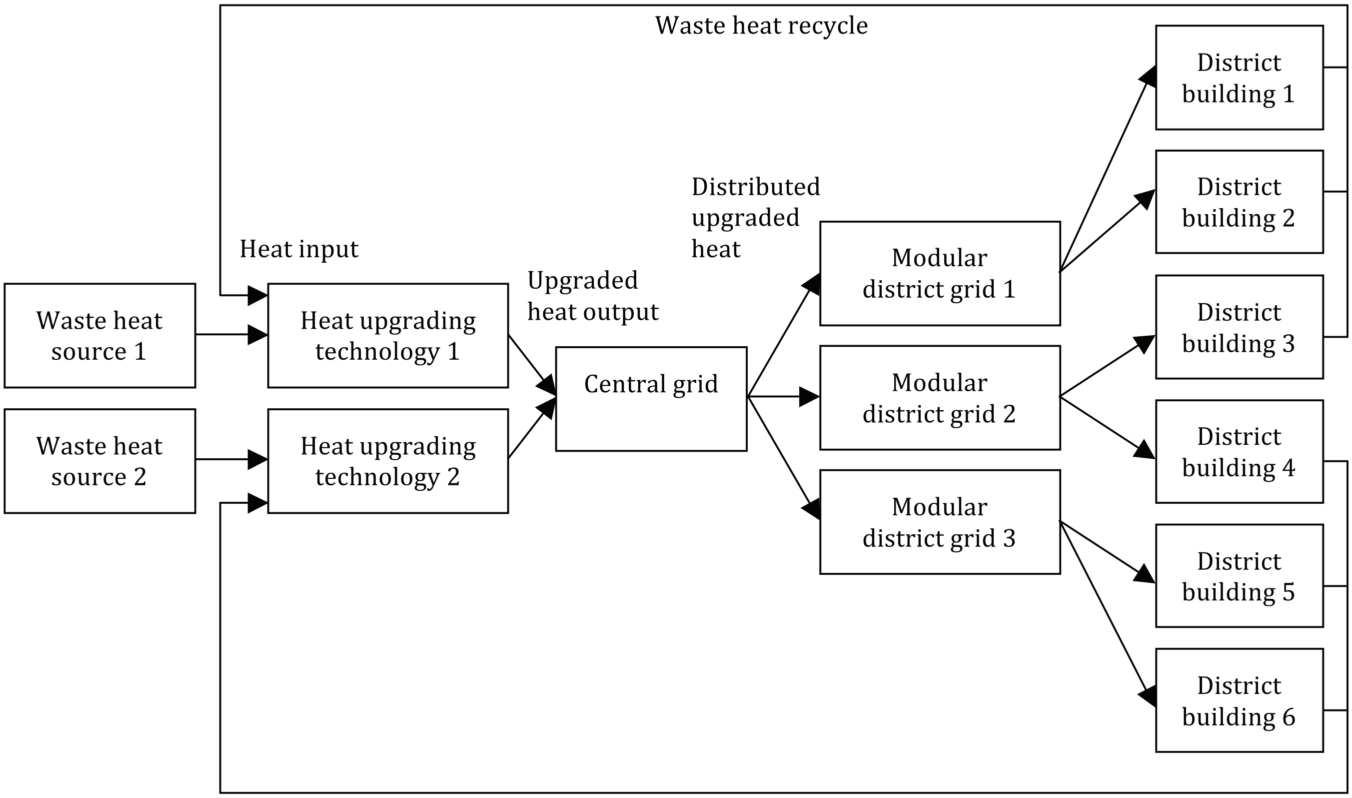


Figure 4. System diagram of the district heating system (Ajah, Patil and Herder 2006)

The waste heat sources represent the heat source while the modular district grid can represent the substation and secondary network for each heat sink. The central grid in this diagram represents the DHS primary network, which may be centralized or decentralized based on the network's optimization and use of heat upgrades.

At a district scale, existing infrastructure can be used to collect waste discharge and apply it to a heat recovery application. Wastewater, for example, is used as a heat source for district heating networks in both a section of Tokyo's DHW production (Yoshikawa 1997) and space heating requirements in parts of Sweden (Balmér 1997).

In buildings housed with commercial or small-scale industrial operations, heat-generating processes can utilize the aforementioned technology to capture thermal energy for heat and hot water needs on-site or off.

2.4.3 Heat Exchange Technology

Ensuring the efficient recovery of waste heat from industrial processes requires a detailed inventory of process characteristics. If heat exchange technology is defined at the source, load losses (given pressure drops in heat exchangers) can be measured and factored into the DHS primary network preliminary design.

Given a scenario where an industrial process is using hot air from a gas-fired furnace, flue gases as a product of combustion can be used to heat water. By using a double-pipe heat exchanger, for example, the efficiency of a number of different flow configurations can be assessed including parallel flow, counterflow, or shell-and-tube.

The efficiency is effectively a ratio of actual heat transfer rate to maximum heat transfer potential. For crossover flow, the efficiency can be calculated using equation 3 (ASHRAE 2005).

$$\varepsilon = \frac{1 - \exp\left[-N(1 - c_r)\right]}{1 - c_r \exp\left[-N(1 - c_r)\right]} \qquad 3$$

Where N is the number of fins in the heat exchanger and c_r is the capacity rate ratio described as the proportion of minimum fluid capacity rate (in W/°K) to maximum fluid capacity rate.

For further discussion on calculations of heat transfer and heat exchanger effectiveness for various industrial applications, consult Appendix 1 as well as (ASHRAE 2005) or (EMR 1985).

2.4.4 Waste Heat Production

An efficient method of identifying waste heat potentials in any industrial or commercial facility is by performing an initial mass balance for the buildings and processes. In such an analysis, an inventory of material and energy flows is established and values for inputs and outputs are recorded (Guyer 1998). While many of these outputs are commonly considered wastes, with associated expenses for their treatment and disposal, they can actually be regarded as value-added byproducts.

Recycling of waste heat to other on-site processes is an obvious use of residual thermal energy. Assessing the feasibility of recycling, upgrading or converting waste heat for on-site industrial use is beyond the scope of this research. Nevertheless, dependent on scale and processes involved, a facility may have excess thermal energy after the process requirements are satisfied or the quality of a waste stream is not useable.

For example, a 2003 study by De Monte and Padoano (De Monte and Padoano 2003) examining waste heat recovery in the coffee industry determined that the energy balance of the roasting process confirmed the feasibility of heat recuperation from a high temperature source. The study's authors did, however, make the observation that "the only use for the recovered heat was for the air conditioning of buildings because of scarce energy needs for other plant processes" thereby concluding that "a recovery plant designed only for a seasonable exploitation of waste heat (e.g. for winter heating) could be a very interesting and profitable solution because of a lower investment cost".

A coffee roasting process produces exhaust gases which exit the roasting and cooling stacks at temperatures around 93°C (200°F). Emission byproducts include particulate matter (PM), volatile organic compounds (VOC), nitrogen oxide (NO_x), formaldehyde, and carbon monoxide (CO).

Installing air-to-air heat exchangers, such as heat wheels with a purging section that includes catalytic or thermal oxidizers, can reduce commercial roasting emissions by more than 90% (BAAQMD 2009, Whiston 2009), or save up to 60% of the energy used (Rubinstein 2007) while meeting a fraction of the space heating needs in the area.

Similarly, the commercial brewery—a common feature in many cities—has opportunities for waste heat recovery. Wort boiling, which consumes as much as 20% of the total energy in a brewing facility (Bamforth 2006), can utilize water-to-water heat exchangers to circulate waste heat to other residential uses. Vapor condensers generate hot water by heating the cooled water where the vapors from the boiled wort are condensed and can be cooled in a heat exchanger; the temperature of the heated water varies depending on system controls but is around 80 and 98°C (Briggs 2004). Installing a vapor condenser heat exchanger for volatile organic compounds (VOC) on the brew kettle can serve to capture otherwise wasted energy as hot water, and be circulated in a neighborhood's hydronic heating system. Such a system can recover 40kWh of thermal energy per kilolitre of boiled wort (Ockert 2006).

In a study on large commercial bakeries by (Lukitobudi, Akbarzadeh and Johnson 1995), air-to-air heat exchangers using thermosyphon heat pipes, with water as the working fluid, were tested under the medium temperature operating conditions of a bread bakery; the study determined that waste heat could be recovered from the oven flue gas to heat up the proofing oven (where the dough is allowed to rise), providing an annual waste heat recovery of 314.5 GJ/yr under regular operating conditions.

Another thermal process ubiquitous to mixed-use urban areas is the commercial laundromat. A propane tank, located exterior to the site, is connected to a gas-powered water heater in the building; the water heater then heats the hot water for the washers to a temperature range between 15 and 65°C (Sullivan, et al. 2008), in a single or multiple cycle per load. The propane tank also feeds a jet in the clothes dryer's fire box, which heats incoming air; this air is delivered to the revolving drum, dries the clothes, and exhausts hot air to the outside.

As shown in Figure 5, the commercial dryer is a linear energy process that produces an average of 1.5kWh per kg of water evaporated for a typical drying cycle, with 0.3kWh of thermal energy required simply to heat up before the first cycle. In other words, roughly half the energy supplied to the dryer is dissipated as waste heat.

Figure 5. Commercial laundromat energy flow from propane to hot air exhaust

Commercial laundromats can employ air-to-water heat exchangers in their drying cycles. As the dryers typically exhaust their hot air through a series of different vents, a run-around system –with heat recovery efficiencies of approximately 65% (Sweatman 2007)- could be installed without requiring major changes to the ductwork. By employing a series of water coils, one in each of the dryer exhaust ducts and one in a fresh air intake manifold, a circulation pump could then pipe an aqueous solution (i.e. any heat transfer fluid such as a glycol-water mixture) from the hot exhaust stream to the cooler fresh air stream entering adjacent buildings.

In Canada, approximately 86% of households have a clothes dryer with the majority of these being a standard 125-litre size (NRCan 2010). Each dryer, over a typical cycle, emits 150 cfm (ft^3/minute) at approximately 57°C for 30-60 minutes. This may not seem like a great deal of heat given average household usage profiles in Canada but with a low-temperature heating approach, i.e. lower exergy systems, in their mechanical systems (Ruest 2000) there is the potential for significant energy savings and GHG mitigations.

There is also the option of upgrading the exhaust air with heat pumps, some of which feature upstream recuperators (i.e. heat pipes or cross-flow systems). The heat recovered can be then transmitted to the intake air or DHW needs using temperature control systems (Fehrm and Reiners 2002), which will be discussed later.

As previously discussed, some jurisdictions around the world have recognized the need for such energy schemes in their planning phase. The community of Cerdanyola, Spain, for example, prides itself upon novel energy cascading processes and has developed complex energy systems-based polygeneration (Pol 2009). Polygeneration refers to any energy supply system that provides a multiplicity of energy forms, such as a trigeneration (electricity, heating, and cooling) plant (Concerto 2009).

Apart from a 46MW_e natural gas cogeneration facility, the jurisdiction of Cerdanyola exploits thermal energy from heat-generating systems such as biogas combustion, solar collectors, and agricultural processes; these technologies are interlinked by a "communal energy management system (CEMS) that integrates supply and demand…to optimize the system exploitation" (Polycity 2007).

Similarly, the Burgholzof project applies a low-energy planning approach to 800 residential units and a school in the city of Stuttgart, Germany. The community has been set up with a solar-supported local district energy network (Erhorn 2010) and approaches future development with an exergetic-efficiency type analysis with time-specific GIS household consumption data (Concerto 2009).

2.4.5 Cross-Optimization

Of particular interest for waste heat recovery are mixed use areas, common to all cities, which are most prevalent in the first three archetypes of the urban environment: the city centre, edge of centre, and inner city districts. The other four archetypes provide opportunities for heat cascading to urban demand.

A framework known as 'urban harvest' examines any opportunities, of which many exist, for collecting local resources and recycling waste heat or waste fuels within the urban jurisdiction (R. Rovers 2007). The principles of such an approach tend to focus on four distinct strategies: multi-sourcing, cascading, quality upgrading via recycling and quality upgrading via closing loops (Rovers, Agudelo and Mels 2009).

Urban energy, as understood through this lens, can be discussed by looking at the exergy and, more specifically, the exergetic efficiency of a jurisdiction.

Exergy, is both a quantitative (kWh or GJ) and qualitative, such as steam or hot water media, indication of the energy utilized. Total exergy is the sum of all types of exergy (including chemical, physical, and kinetic) that are associated with a considered mass flow (Dincer and Rosen 2007). It can be considered by the ways in which services and processes convert energy to a form with reduced exergy.

A frequently cited example of this is the utilization of coal (the source), converted to generate electricity (the carrier) that, subsequently, is used in resistance heaters to heat a home (the service) during the winter months (NRCan 2007). While the energy is considered to remain constant, the exergy is significantly decreased throughout this sequence.

A system's exergy efficiency is the ratio of exergy demand to exergy supply; the difference between both variables is the entropy, or molecular disorder, increasingly produced within the system (ASHRAE 2005). In the same way that systems and process engineering designs boilers to minimize entropy generation, urban energy planners can think of the city as a large energy-using system with a set of exergetic demands. Figure 6 illustrates the source and end-use entropy cascades common within a city.

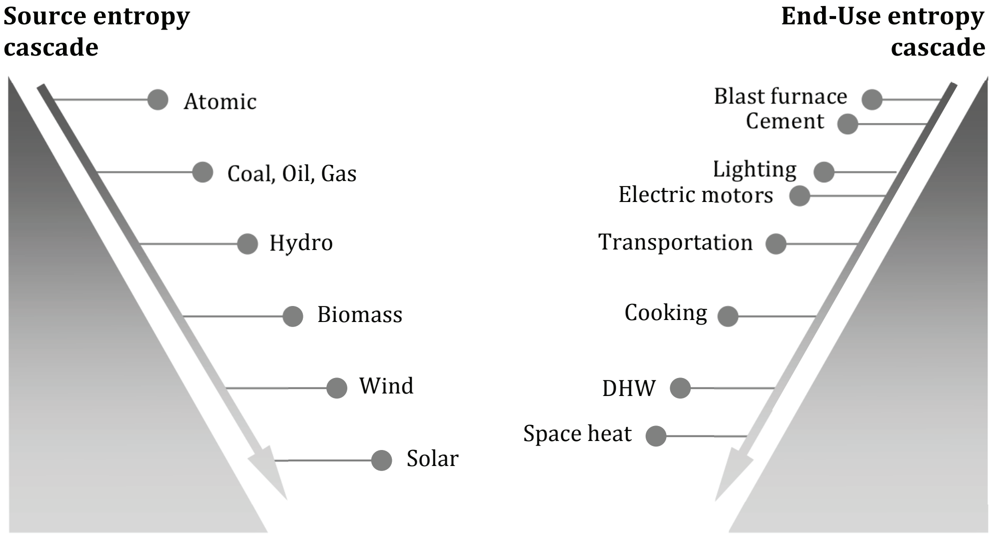


Figure 6. Entropy of source (supply) and end-use (process) in the urban environment (NRCan 2007)

As shown in Figure 6, there is a range of end-uses with increasing degrees of entropy, suggesting opportunities for a cascade of exergetic potential in a city system. However, exergy analysis is typically absent from heating analysis within such a context. End-use for power as well as low-to-medium and high-grade temperature demands are supplied by a varied range of carriers and mostly hydrocarbon-based energy sources. Hence, as described by (Fisk 2006):

> The exergy analysis, as usual, is inviting us to look out of the box. The inefficiency is coming from mismatched temperatures and they are cured, at least in process industry, by heat recovery systems and inter-mediate temperature storage… Assuming resistive heating has been removed altogether, the urbanization advantage is that the demands are feasibly within reach of each other for cross-optimization.

One approach to cross-optimization of networks, such as HVAC or electrical, between buildings or sub-systems in a city is through energy potential mapping. A departure from ‘traditional’ energy analysis of the built environment, which considers process efficiencies and performance of individual buildings, energy potential mapping considers spatial functions and local qualities of a jurisdiction (Dobbelsteen, et al. 2007) in order to identify opportunities for cross-optimization of sub-systems.

Cross-optimization reflects an approach to urban planning, known as *connectedness*, that can often contradict the segregated and slow-moving environmental decision-making process common to many cities (Hester 2006).

In order to cross-optimize, urban planning must take an approach that not only matches energy load to demand, but does so in the most appropriate qualitative, temporal, and spatial form. In other words, adopt a low-ex, or 'low-exergy', spatial planning approach that "locates heat-demanding premises close to waste heat producing industries, or introduces a cold-requiring (thus waste heat producing) facility in between heat demanding functions" (Dobbelsteen, Dorst and Timmeren 2009).

Heat cascading is already common in industrial applications; most typically with combined-cycle power generation systems that use the steam generated from a gas-fired turbine to drive a second turbine (Kaya 1997). While low-caloric heat is most useful when distributed over short distances (Dobbelsteen, et al. 2007), measuring heat cascading potential is an important low-exergy analytical approach to energy planning in a mixed-use setting.

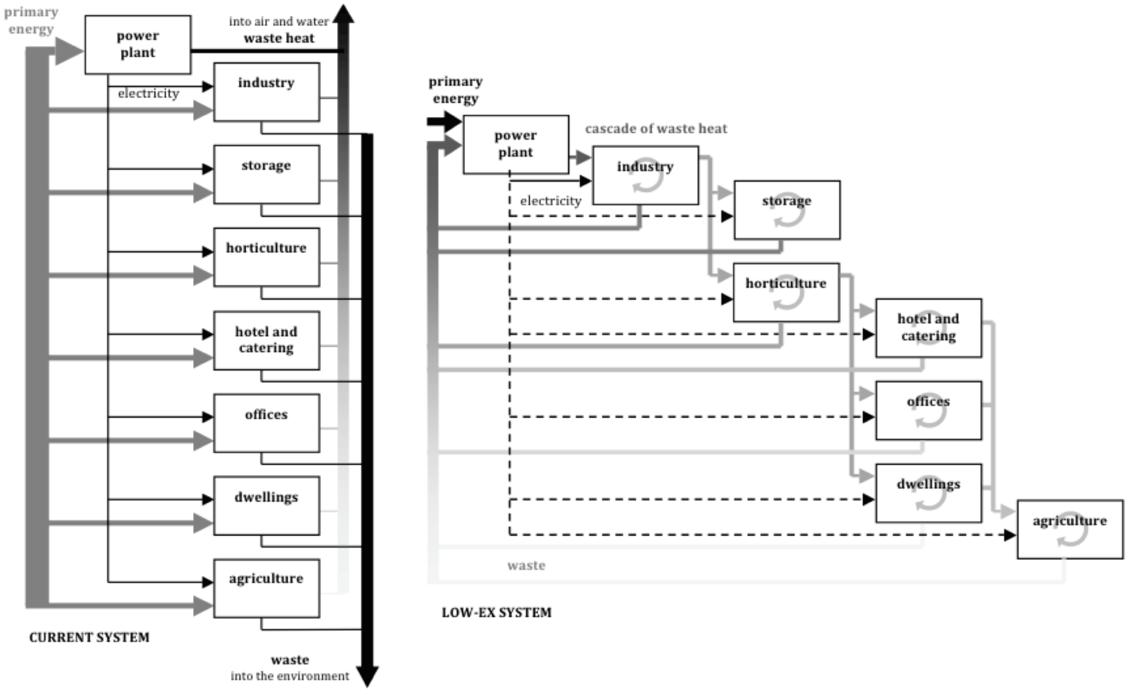


Figure 7. Typical urban energy system versus a waste-heat optimizing energy system (Dobbelsteen, Dorst and Timmeren 2009)

Figure 7 exemplifies some of the distinct processes where a heat cascading approach can be taken in an urban area that includes industrial, commercial and/or residential energy systems.

Noteworthy, is the entropy cascade associated with the energy mix used in the various processes of a city's systems. Typically, as described in the coal-to-resistance-heater example, there is a significant mismatching of low-entropy fuel sources with high-entropy end-use.

2.5 Thermal Storage

In assessing the applications for waste heat recovery, parasitic, standby, and distribution losses need to be accounted for. The need for optimizing heat management and storage systems is a key factor to counteracting standby losses and improving overall system efficiencies in heating systems (Bell 2005).

Temporal and spatial limitations must be addressed when identifying sources of waste heat for the DHS. Spatially, the distance (and thus, appropriate carrier) between waste heat supply and energy demand is of critical importance in the assessment.

In regards to temporal considerations, load-matching in mixed-use areas can be a challenge. Industrial occupancy or processes and residential habitation or activities often happen conversely over the course of a day, weekends notwithstanding. While much of the waste heat is being produced by the industrial process in the mid-day, tenants are away from their home; when people are home in the mornings and evenings, many businesses are closed.

Thermal energy can be stored in a variety of forms, depending on the heat-generating processes. For example, a district waste heat technology might store its source load using a heat pump or some thermal mass. By providing a store for the process waste heat, the heat energy can be collected and conserved until it is most useful.

Geothermal boreholes, residential water tanks, or shallow aquifers all represent potential forms of intermediate temperature storage for waste heat.

In the case of water-heating applications, point-of-use (i.e. tankless) hot water systems are the least energy intensive (Peckler 2003), when compared to any temporary storage media such as central tanking with conventional, or even radial, piping. So it is of fundamental importance to minimize the distances between hot water sources and their point-of-use.

Where this is not possible, it is worth considering storage options for use of waste heat towards supplying DHW or SH needs in a multi-zoned city district. For example, storage tanks with heat pumps or heat exchangers that already optimize thermal stratification (Harvey 2006) can be employed.

The three main types of storage media for multi-unit areas are aquifer heat stores, plastic-lined gravel-water mix pits, or concrete and steel hot-water tanks. In all cases, the storage containers are completely or partially in the ground to minimize heat loss via insulation.

The breadth of literature on the performance of thermal energy storage systems when integrating load balancing, shifting peak to off-peak loads, or using waste heat loads (in place of thermal generation plants) is narrow. Optimizing storage size and media for district heating systems is further discussed in both (Dinçer and Rosen 2002) and (Bruno, et al. 2010).

2.6 Buildings of a Mixed-Use Jurisdiction

The urban areas defined earlier in Figure 3, can be classified generally according to their energy use or exergetic potential. Again, these areas are the city centre, edge of centre, inner city districts, industrial estates, suburban districts, urban extensions, and rural hinterlands (Dodd 2008). A more accurate characterization of energy use, however, requires establishing and examining categories at a smaller scale.

These areas can be further subcategorized by land-use or function. Their functions include built-up areas (i.e. residential, retail, hotel and catering industries, public services, social or cultural services, and business areas); semi built-up areas (i.e. graveyards, waste dumps, scrap yards, and construction sites); recreational areas (i.e. parks, public gardens, sports fields, urban gardens); and roads (Leduc and Rovers 2008).

All land-use categories possess options for waste heat recovery. Of particular interest to the end-use analysis of this research, however, are the built-up areas; as total energy use for buildings has the highest end-use in space heating and hot water. Similarly, notwithstanding transportation, the commercial and residential sectors represent the largest total energy end-use sectors (CEM 2007) in the urban environment.

The building categories for consideration within built-up areas are residential, commercial and institutional (R. Rovers 2007). To establish energy profiles, these categories can be sorted further by building type and vintage. Estimating energy loads accurately requires building data. However, discussing larger classifications of end-use sinks (i.e. by land-use, function, or urban area) facilitates a harmonization between urban planning objectives with energy potential mapping, as described earlier.

The housing types of the residential category in the urban environment, for example, are single detached houses, double/row houses, low-rise apartments, high-rise apartments and mobile homes. Their proportionality in the housing mix will affect the types of heat recovery applications and opportunities that can be considered.

Cities are not all built the same, of course, and what might seem common in one is quite different in another. Within Canada, for example, single detached houses represent on average 58% of all dwelling types in urban areas (NRCan 2010). However, while in a city like Calgary they are more than 61%, in Montreal they are less than 32% (Grammenos 2005).

2.6.1 Building Loads Estimation

Collecting and accurately analyzing end-use energy data is a key component to assessing a DHS. Within a comprehensive survey of end-use loads, energy demand factors of consideration for buildings potentially served by the system include: present and future growth in energy use, daily and seasonal variation in demand, retrofit requirements for DHS connection, and base-load, back-up and peak requirements for buildings (Arkay and Blais 1996).

Of interest to a DHS is the portion of building energy used towards SH and DHW. Figure 8 illustrates energy use subcategorized into housing types by end-use.

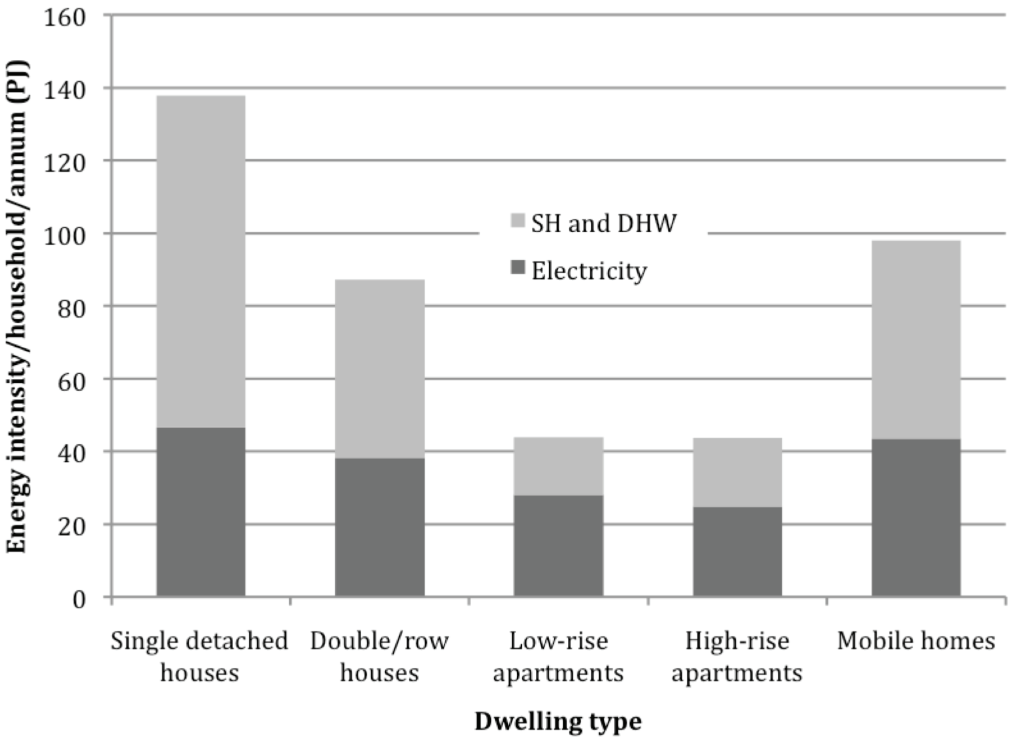


Figure 8. Energy intensity for Canadian households by dwelling (NRCan 2010)

As seen in Figure 8, single detached houses in Canada have more than three times the energy intensity than low-rise apartments. Of particular note is that space heating and hot water represent decreased proportions of total energy intensity in multi-unit buildings, as compared to single unit buildings; the former being highest at 66% and the latter being lowest, 36%, for low-rise apartments.

Heat infiltration between ceilings, floors and walls among multi-unit multi-storey buildings is a feature common to most cities. Ground floor flats typically show the highest infiltration rates, given leakage distribution on the building envelope (Feustel and Lenz 1985). The overall air changes, indicative of the building envelope's energy efficiency, are comprised of forced, infiltration and natural air change elements.

A coarse-grain method to estimate the demand factors of a building is based on using established indices of average and peak heat demand per unit area for various classifications of buildings (Scheweig 1997); in other words, a heat demand per unit area is multiplied by the total heated area to determine total demand. Both coarse and fine-grain methods are described further in Chapter 3.

Conversely, fine-grain analysis involves conducting detailed field surveys on heat demand to establish thermal base-loads and building characteristics for the jurisdiction. Sample data collected from model buildings can be used to calibrate thermal loads for other buildings of the jurisdiction (Coles 1990) and assess the feasibility or preliminary design of the DHS.

2.6.2 DHS Interconnections

As previously described in section 2.4.1, a DHS involves a primary and secondary network. The consumer interconnections included as part of the secondary network are either direct or indirect (Arkay and Blais 1996). A direct connection describes a network where steam or hot water is directly transferred to the end-user; or where primary and secondary networks share the same media. An indirect connection describes a network where the primary network media and that of the secondary network are isolated from one another and heat exchangers are used to transfer energy.

The heat exchange units and heat conversion technologies that comprise the secondary network of a DHS (as well as those at the heat source end) are too many to discuss in further detail within this research.

For further information on DHS secondary networks and their design, the discussion in (Skagestad and Mildenstein 1999), (Snoek, et al. 2000), and (Zinko 2008) can be consulted.

2.7 Summary

In this chapter, the central themes to the research were introduced as energy use in the city, district energy systems, and waste heat opportunities in mixed-use jurisdictions. The literature on these themes was reviewed and considerations influencing a method design for identifying waste heat sources and developing a design for a preliminary DHS primary network were discussed.

CHAPTER 3 : DESIGN AND METHOD

By considering the availability of residual thermal energy and the heating demand in mixed-use settings, planning processes can begin matching potential loads within the DHS network to be designed. As such, an assessment tool is necessary to identify the thermal energy sources and sinks and to design a primary network to connect the sources and sinks.

In this chapter, the method is discussed and its associated assumptions and calculations explained.

3.1 Method Overview

The proposed method is to identify sources of waste thermal energy from industrial and commercial processes and establishes a preliminary design for sequencing of a district heating primary network for sinks in mixed-use jurisdictions. The design is based on a cost-minimization algorithm and applied to the financial costs of developing the primary network pipeline. The method then calculates the GHG emissions reduced by such a DHS network design.

The method is divided into two phases, the first phase describing a method to identify the sources and sinks, and the second phase a method to design a preliminary DHS primary network.

In the first phase, the potential heat sources and sinks are geographically identified using a technique known as energy potential mapping with GIS spatial analysis. The heat sources are those processes in the jurisdiction with residual thermal energy. The heat sinks are cluster demands—the SH and DHW demands for buildings or sites geographically grouped together—in the same jurisdiction. This is the ‘screening’ or identification phase of the method.

In the second phase, DHS primary network sequencing for building space heating and hot water loads is obtained, based on a cost-minimization algorithm. Reduction in GHGs and total cost of the primary network are produced; attributes of the sources and sinks such as distance and optional heat stores or upgrades are defined. This phase is referred to as the method's 'preliminary design' component.

Figure 9 illustrates a context diagram for the system, with the associated phases. The flows for this DHS are thermal energy using hot water as a medium.

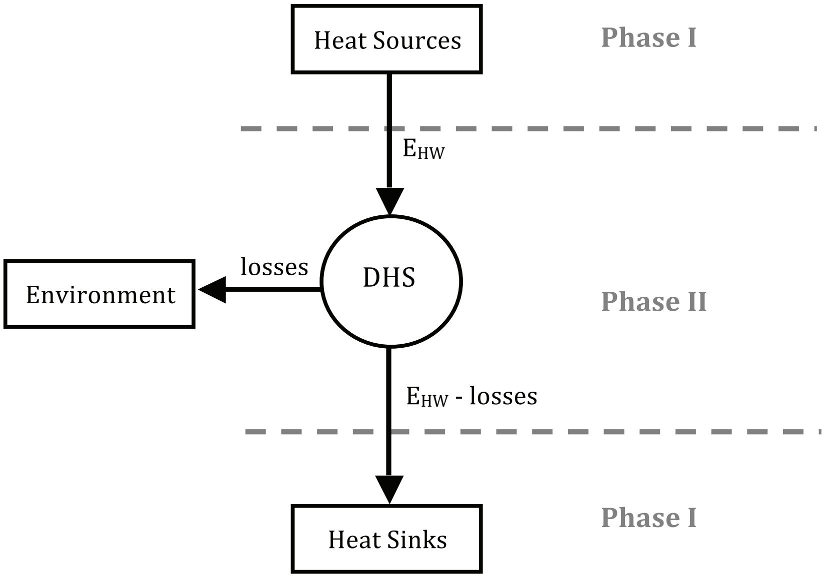


Figure 9. DHS context diagram

The prioritization of source types, sink cluster characteristics, thermal stores, or siting of heat upgrading technologies can be predicated on jurisdiction-specific features, including behavioral norms, land-use and zoning regulations, and environmental policy input by the user and, thus, applied to the system.

As an approach intended for planning, the method is spatial in nature to facilitate visualizing of the optimized network for the jurisdiction.

The analysis can further be divided into three-layers (Schulze 2010), with layers representing steps of the phases, to identify sites and optimize the network of the DHS. Figure 10 illustrates these layers.

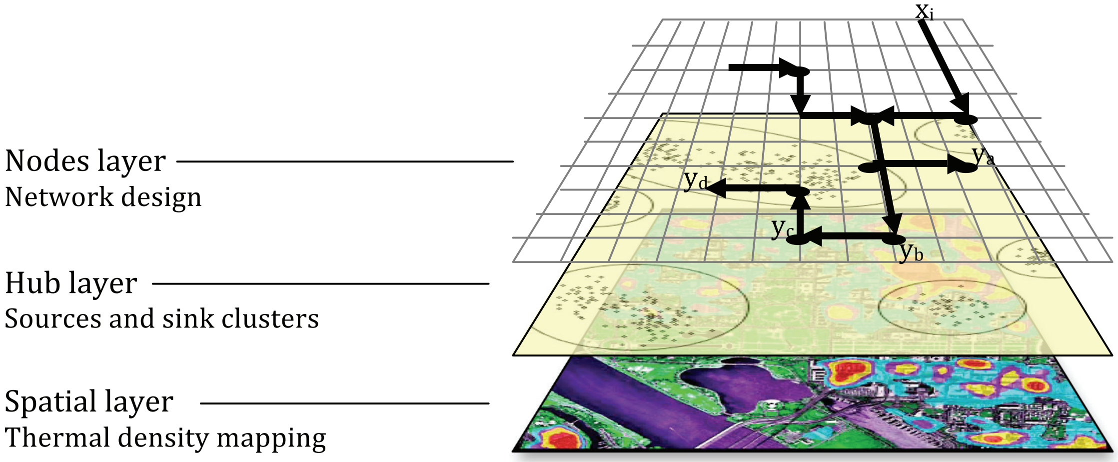


Figure 10. A graphical representation of the two phases

Beginning from the bottom-most layer (i.e. spatial), the spatial data is used to map thermal density and locate sites of waste heat-generating processes in the selected jurisdiction. Similarly, household data on energy-use and building performance is gathered for the jurisdiction. Using GIS spatial data, the layer identifies potential sources and sinks within the mixed-use urban landscape for further investigation of process streams with waste heat. This layer is used as part of Phase I, or the identification component, of the method.

In the middle layer, the spatial data is analyzed to produce clusters based on supply and demand co-locating sites or buildings and identifying opportunities for sequencing. These clusters may also represent priority households based on user characteristics defined by the jurisdiction. This intermediary step simplifies the spatial representation of sources and sinks. This layer also corresponds to Phase I, or the identification component of the method.

Finally, in the top layer, a grid is overlaid upon the previous layer to establish nodes corresponding to the clusters of sources and sinks, and arcs corresponding to possible connections between the nodes. In other words, in GIS terms, arcs are paths along a network grid and nodes are the vertices along, at the start, or the end of the arcs that indicate the beginning and end of each arc.

The method is intended for jurisdictions with a set of energy or GHG-related targets prioritized by municipal officials or neighborhood stakeholders. Therefore, the path determined by the network preliminary design is based on selection criteria for the distribution network. These criteria can either be based on matching load profiles based on building types of the sink cluster, for example, or maximizing exergetic efficiency in sequencing of the thermal energy. The network path's efficacy can be assessed based on the amount of conventional fuel displaced for the SH and DHW needs of the sinks being served or the GHG emissions saved for the entire jurisdiction (compared to maintaining use of the same conventional fuels). This layer corresponds to Phase II of the method, in that it is used to develop the preliminary design of the DHS primary network.

The weights or values associated with each arc—being financial cost and thermal energy shipped along the arc, in this case—in the network correspond to spatial coordinates, which can be used to illustrate the network path for the DHS.

An explanation of each phase follows. First, the identification component (i.e. bottom and middle layers) and, second, the preliminary design component (i.e. top layer) are discussed.

3.2 Phase 1: Identification Component

At the outset, the boundaries for the jurisdiction must be defined by identifying and defining heat sources and sinks (see discussion in Appendix 1 for details).

The associated steps require the acquisition of thermal remote data, building energy use data, and industrial process data.

3.2.1 Sink Cluster SH and DHW Load Profiles (Spatial Layer)

Within a district heating system, a range of building types can be served, examples of which are listed in Table 3.

Table 3. Building types and activities served in a DHS network (Lokuch 1980)

Sector	**Building types** (selection)	**Heat-demand activities**
Commercial	Warehouses Semi-detached	• SH and DHW • Telecommunications equipment
Institutional	Multi-functional (e.g. Recreation Centres, Hospitals, Schools)	• Pool facilities • SH and DHW
Residential	Single detached Semi-detached Apartments	• SH and DHW

To identify heat sink clusters formed by buildings within the jurisdiction, building SH and DHW demand and load profiles must be examined.

The method for determining heat sink clusters is illustrated in Figure 11 and described below. Annotating the steps in Figure 11, data on building energy end-use indices (e.g. average heat load or SH and DHW demand per unit area) are sorted according to building archetype to develop energy-use profiles.

The dashed boxes in Figure 11, represent optional energy use intensity components to the methodology as described in Appendix 2. Following the method outlined in Appendix 2 can result in a more fine-grain analysis, as described in section 2.6.1 and discussed further below. A method excluding these components can be considered as a more coarse-grain analysis.

This data is then categorized according to the geographic coordinates corresponding to the datasets; it is organized according to building types in the land parcels for the jurisdiction (i.e. number of buildings or area of buildings by type for each parcel). Finally, as described further in section 3.2.3, the individual sites or buildings are formed into clusters using spatial statistics analysis.

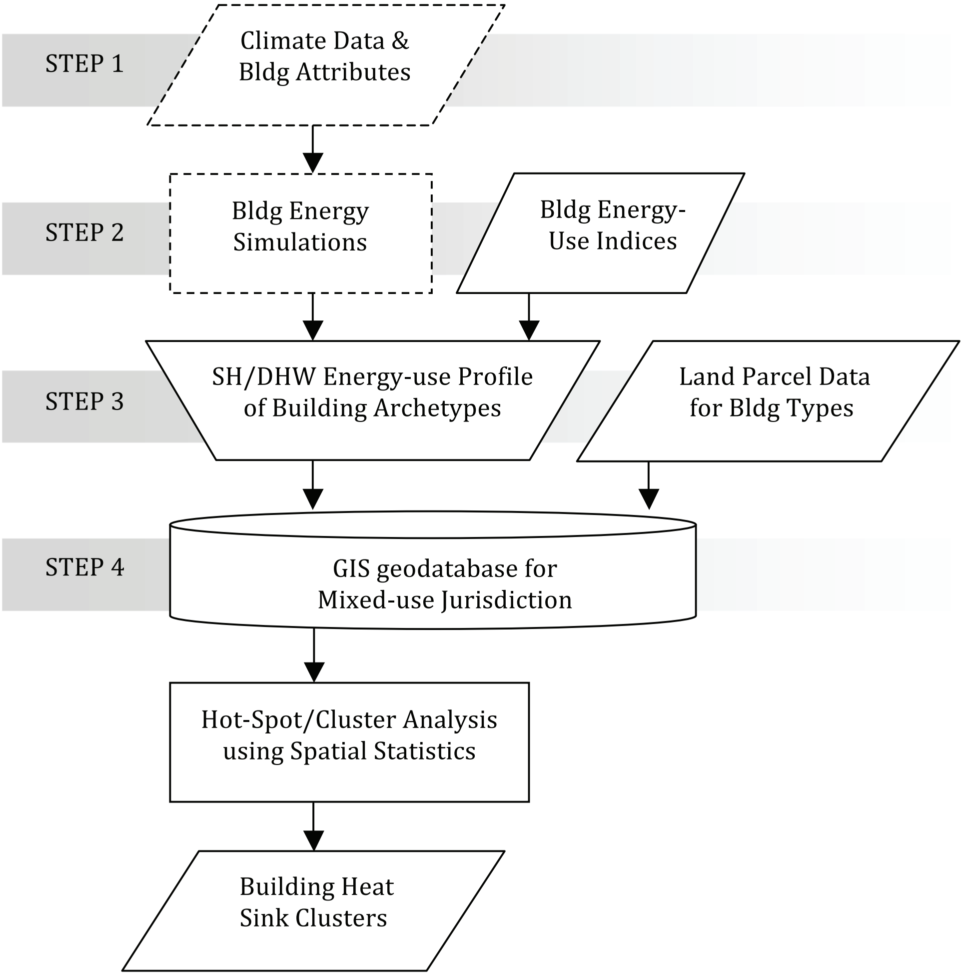


Figure 11. Flowchart for developing heat sink clusters

Datasets are required on household energy audit performance for model houses of known building types within the jurisdiction. Such archetypes have energy indices that can be categorized by vintage (i.e. period of construction) and dwelling type. For example, drawing on research for Canada done by (Farahbakhsh, Fung and Ugursal 1997), twelve archetypes can be selected for single-detached homes based on number of storey's and vintage.

Model houses sharing the same archetype are compared and validation of energy-use values is conducted using databases for the country or larger administrative divisions (i.e. districts, provinces or states), where available.

To more accurately determine energy-use, characteristics of the building envelope, local climate, and HVAC systems for the model houses is required. Most certified energy auditing organizations within the jurisdiction would store such datasets.

Climate, and external temperature changes throughout the year, is one of the largest determining factors for household energy demand. This can be addressed using the degree-hours model, which can account for average set-point temperatures of the DHS sink building(s) as well as outside temperature.

In the degree-hours model, for each dwelling type, the associated degree hours are calculated to account for such seasonal variations using equation 4 (Ajah, Patil and Herder 2006).

$$DH = \sum_{l-1}^{l} \left\{ \left(T_d - T_e \right) \tau \right\} \qquad 4$$

where: DH = degree-hours
T_d = set-point indoor temperature (ex. 18°C)
T_e = external temperature for jurisdiction's climate (°C)
τ = hours for which the difference of $T_d - T_e$ is positive

Climate data is available through most national meteorological sources. However, default climate datasets are typically included in energy simulation software, illustrated as step 2 of the flowchart in Figure 11.

Next, the data is used to calculate the energy intensity and heat load profiles for the building types. Further discussion on this can be found in section 3.3.2 or by referring to Appendix 2.

Similarly, a building's hourly energy demand can be compared between common building types, or other selected parameters, to establish an hourly energy demand profile. A simplified flowchart for building energy intensity and the equations associated with developing energy indices for individual buildings are described in Appendix 2.

Once the energy consumption and demand profiles are determined for the selected archetypes, datasets on building archetype density by tract can be determined for the jurisdiction. This, then, generates a simplified indication of energy use profiles for the jurisdiction, by tract.

3.2.2 Industrial and Commercial Heat Load Profiles (Spatial Layer)

Having defined the jurisdiction's boundaries, an inventory of its possible waste heat sources is needed, according to their geographic coordinates, using a geographic information system (GIS).

Within the mixed-use jurisdiction, there exist myriad opportunities that can potentially supply district heating systems. These may include principal sources such as CHP plants, where heat and electricity are co-produced by a utility, and incidental sources where process heat from industrial operations can be exploited for SH and DHW use. There is also the use of renewables, such as solar thermal, which can be integrated into a more complex district heating system.

The capacity of the facilities generating process heat is important; however, given that they are simply allocating whatever thermal energy they would otherwise have generated, the assumption is that these load "plants" do not greatly influence the electric power network load.

Depending on the demand and load profiles of these plants, as well as the temperatures required for facility processes, and those discharged from the plant, the site may be a source or a sink along the sequence.

It is important to begin considering the characteristics of thermal energy collected and calculated for these sites as weights associated with the nodes, as this will be applied during the Nodes Layer discussion.

Thermal Remote Data

Thermal remote sensing data is required to calibrate surface temperatures for determining 'hot spots' of waste heat in the jurisdiction. With orthorectified imagery, geometrically corrected for uniform scale, ETM+ imagery for Band 6 (i.e. the thermal band) can be first converted to spectral radiance by calculating (NASA 2009), as shown in equation 5.

$$L_{\lambda} = \left[\frac{(LMAX_{\lambda} - LMIN_{\lambda})}{(QCALMAX - QCALMIN)}\right] \times (QCAL - QCALMIN) + LMIN_{\lambda} \tag{5}$$

where:
L_{λ} = Spectral radiance in watts/(m^2×ster×m)
QCAL = Pixel value in DN
LMIN_{λ} = Spectral radiance scaled to QCALMIN for low or high gain in watts/(m^2×ster×µm)
LMAX_{λ} = Spectral radiance scaled to QCALMIN for low or high gain in watts/(m^2×ster×µm)
QCALMIN = Minimum quantized calibrated pixel value in DN
QCALMAX = Maximum quantized calibrated pixel value in DN

This is subsequently calibrated to surface temperature, assuming a surface emissivity[*] of 1 (Oke 1988), using equation 6.

---

[*] Emissivity describes the ability of any surface to radiate energy (Collins 2003). The areal surface emissivity of urban jurisdictions is a complex task (Oke 1988). Using a surface emissivity of one, otherwise described as 'unity emissivity', implies that the ratio of radiant flux emitted per unit area is equal to that of a temperature-equivalent black body.

$$T = \left[K2/\ln(K1/L_\lambda + 1)\right] - 273.15 \qquad 6$$

where: T = Surface temperature in °C
L_λ = Spectral radiance in watts/(m^2×ster×µm)
$K2$ = Calibration constant 2 for Landsat imagery in Kelvin
$K1$ = Calibration constant 1 for Landsat imagery in watts/(m^2×ster×µm)

The resulting thermographic imagery provides a visualization of hot spots where low-to-medium grade heat is either lost through building envelopes or expelled through discharge points. This also provides a temperature range at which waste heat priorities can be ranked and investigated further.

Waste heat sources can be spatially identified by means of detecting anomalies in average surface temperature within the mixed-use jurisdiction. They can then be defined through examining discharge rates and temperatures as well as establishing a database of typologies for commercial or industrial processes.

These waste heat sources can be derived from a number of heat-intensive processes involved in commercial or industrial facilities common to mixed-use jurisdictions, as listed in Table 2. Where specific data on process heat from potential facilities in the jurisdiction is unavailable, datasets on industry standards based on operational scale are available through research organizations such as the Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC). As access to process data on industrial operations is restricted under proprietary policies, descriptive statistics and averages can be used where available.

Data on wastewater effluent discharge may also be collected from municipal wastewater services. This can determine levels of heat availability to the DHS.

Exergetic Potential

The primary means of classifying and quantifying waste heat sources of a DHS is through measuring its energy, in terms of thermal loads, as described in Figure 9.

A second approach to heat classification and quantification of sources is through measuring the exergetic potential of the facilities in the jurisdiction. Modeling systems of waste heat for direct low-temperature use based on exergetic flows provides an approach thermodynamically advanced over primary energy conversion of high-exergy fuels to SH and DHW use (Ajah, Patil and Herder 2006). As described in Chapter 2, total exergy in a process is defined as the sum of chemical, kinetic, physical and potential components of the system.

For any DHS, exergy can be considered based solely on the physical component since, unless chemical processes such as salt/ammonia vapour heat pumps are used (Spoelstra, Haije and Dijkstra 2002), all three other components are negligible (Ozgenera, Hepbasli and Dincer 2005). The exergy available in a defined quantity of district heat is calculated with equation 7.

$$Ex = Q(1 - T_o) \Big/ \Big[(T_i - T_o)\ln(T/T)\Big] \qquad 7$$

where:
Ex = exergy of heat medium (MJ)
Q = heat transfer associated with the flow mass
T_i = temperature in (°C)
T_o = temperature out (°C)

Input and output temperatures, and the exergy as a result, within the DHS are a function of the system's ambient temperature. According to (Dincer and Rosen 2007), for example, when outside temperature exceeds 2°C, T_i is held at 85°C and is increased in inverse relation to the outside temperature to a maximum of T_i = 120°C (at –20°C).

As shown in Table 4, an inventory of processes must eventually include a description of the stream type, temperature, flow rate; using exergy can assist in matching heat loads with cluster demand types.

Table 4. Examples and characteristics of commercial or industrial processes in mixed-use jurisdictions (Bamforth 2006, Fadare, et al. 2010, Tucker, Tena and Quarini 2007)

Facility and Processes	Media of Rejection	Averages		Exergy (MJ)	Exergetic heat load (kW)
		Stream Temp (°C)	Mass Flow (kg/s)		
Coffee Roaster					
Commercial roaster	Air	370	0.08	-	29
Microbrewery (1.7 x 10^6 hl/yr production)					
Pre-mash and mash cooking	Steam		-	76	-
Mash filtration	Water	80	-	534	-
Wort boiling	Steam	150	-	86	-
Wort cooling	Water	98	-	70	-
Bakery					
Rack oven	Air	129	0.38	-	42
Hot air food drier	Air	60	31.84	-	1,282
Continuous steamer	Steam	100	0.17	-	56
Continuous oven	Air	186	0.17	-	29
Finished product cooler	Water	30	7.00	-	293
Refrigeration (vacuum condenser cooling loop)	Water	45	28.00	-	2,927
Laundromat					
Tumbler Dryer	Air	150	-	-	-

3.2.3 Cluster Analysis (Hub Layer)

Cluster analysis in GIS analysis allows the user to visually identify source and sink sites within the jurisdiction and group them together.

This analysis identifies clusters of features with high or low values in the dataset, in relation to adjacent features. To complete this task, the Getis-Ord Gi* statistical method can be applied to the weights or values assigned to the sites based on the equation 8 (ESRI 2010).

$$G_i^* = \left(\sum_{j-1}^{n} w_{i,j}x_j - \overline{X}\sum_{j-1}^{n} w_{i,j}\right) \Big/ S\sqrt{\left[n\sum_{j-1}^{n} w^2{}_{i,j} - \left(\sum_{j-1}^{n} w_{i,j}\right)^2\right] \Big/ n - 1} \qquad \text{Equation 8}$$

where:
G_i^* = the Getis-Ord, z-score, local statistic
x_j = the attribute value for feature j
$w_{i,j}$ = the spatial weight between features i and j
n = the total number of features
$\overline{X} = \left(\sum_{j-1}^{n} x_j\right) \Big/ n$
$S = \sqrt{\left[\left(\sum_{j-1}^{n} x^2{}_j\right) \Big/ n\right] - (\overline{X})^2}$

Once the spatial analysis is performed, local statistics are generated for the weighted sites according to their coordinates; the higher statistical values demarcate the waste heat source hubs and heat sink clusters. The coordinates used for the cluster are the nexus of the demarcated areas, signified with either graduated colors or shapes (e.g. circles).

In the case of the DHS method proposed, a cluster would exist where the energy-use profiles for a cluster's building types are high, and the values of its neighboring features are high as well.

If the user chooses to prioritize larger commercial or industrial heat consumers in the jurisdiction, a similar approach can be taken using the respective datasets from the aforementioned sources.

3.3 Phase 2: Preliminary Design (Nodes Layer)

A configuration for a robust DHS based on waste heat sources has been proposed in Figure 4. The model, representing a branched system, can be designed to allow for system flexibility, multiple inputs, and optimization of exergy efficiency in a jurisdiction. The model, however, situates heat-upgrading units before the primary grid, assuming an excess of supply, and distributes heat in a centralized fashion.

To consider this DHS, the heat sources must be properly rated to meet the peak demand of the end-users identified.

If multiple end-users are identified with different heating requirements, the energy can be sequenced to users with lower thermal densities before finally being returned to the waste heat source for polishing and re-use.

Figure 12 illustrates two different approaches to a hypothetical jurisdiction's DHS primary network design.

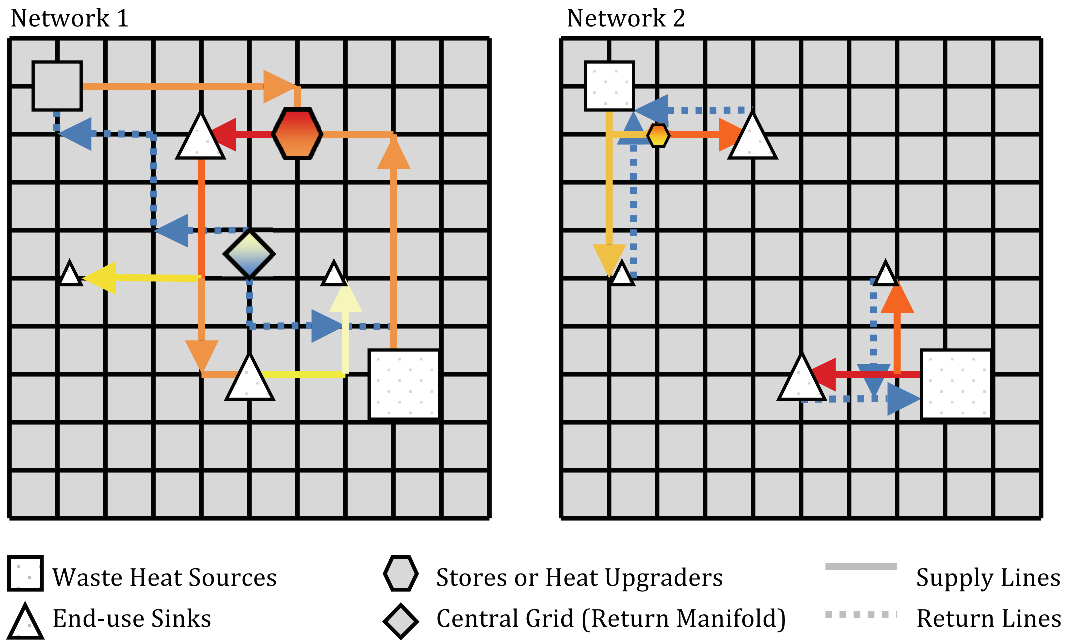


Figure 12. Hypothetical DHS mapping to optimize select targets

As shown in Figure 12, the route a DHS might take can be influenced by source-sink distance, end-user thermal density, and heat upgrading technologies along the DHS. Given cost and GHG targets corresponding to assigned weights, the planner can visualize the route taken by the DHS. Network 1 involves a centralized system that connects all sources and sinks, with different thermal energy loads (and thermal characteristics), through a network of heat upgraders. Alternatively, network 2 illustrates a disjointed and decentralized system of sources and sinks.

Network 2 represents a simplified interpretation of the mapping process that might typically precede a DHS development. Network routing of a potential DHS can be described as traditionally taking a max-flow min-cut approach for network development. This might involve a jurisdiction examining opportunities for proximate waste heat sources, with base load coming from newly established thermal or CHP plants. The utility plant would then operate a control system to assist in optimizing load balancing and respond to peak periods of demand.

3.3.1 Establishing the Network

For any distribution system to be developed, the method must first ensure that sources and sinks connect to one another. This involves building a network with two distinct elements: edges and junctions. In using this terminology, borrowed from transportation-related geometric network analysis, junctions correspond to the street corners in jurisdiction while the edges, or links, represent the streets in between (Butler 2008). These are easily identifiable on most maps.

In energy network analysis, however, the junctions and edges are more simply referred to as nodes and arcs, respectively (Bertsekas 1998). If nodes are considered as heat clusters i and j, then arc (i,j) corresponds to the connection between them.

The junctions correlate to the street corners in jurisdiction while the edges, or links, represent the streets in between. There are two types of nodes: nodes_2, the source hubs and nodes_1, the sink clusters.

As defined earlier, the sink clusters can each be made up of different building types together representing a distinct heat demand profile. Likewise, the source hubs are opportunities for low-to-medium grade waste heat capture, storage, and upgraders. The latter may include boilers, heat pumps, or other upgrading technologies.

Data required in order to assign proper weights to each of the nodes and arcs is identified and defined in Table 5; such data can either be preset or user-defined. Inputs associated with the economic analysis are performed for each DHS primary network.

Table 5. Data inputs for network optimization weights (Reisman 1986, Morofsky and Verma 1979)

Data Category	**Data Type**	**Data Parameters**	**Details**	**Identified in Phase I**
Nodes$_1$: Sink clusters —●— n_1	Demand	- Total annual (MJ)	To identify priority clusters	✔
		- Peak demand factor (MW)	By cluster building archetype	
		- Local climate data (°C)		✔
		- Diversity factor	For improvements and development	
		- Cluster (substation) coordinates	Lat, long	✔
	- *Storage*	- Cost per unit size including capital and operating (\$/m^3)	For peak thermal storage	
Nodes$_2$: Source hubs —◆— n_2	Supply	- Energy medium (e.g. hot water)		
		- Pressure (kPa)		
		- Input temperature (°C)		
		- Return temperature (°C)		
		- Heat content		
		- Source hub coordinates	Lat, long	✔
	- *Upgrade* (TransShip)	- Cost per unit size (\$/MW)	Heat pump for temp. upgrade	
		- Coefficient of performance		
Arcs : Network links ◆——● n_2 n_1	Distribution	- Source, distribution pressures		
		- Transmission loss factor		
		- Pumping cost		
		- Unit piping cost		
		- Fluid velocity constraint		
Optimization Cost				
Financial Cost	DHS	- Escalation rates		
		- Discount rate		
		- Inflation rate		
		- Interest rate on capital		
		- Tax rate		
GHG Cost	DHS	- GHG intensities for construction and operation of DHS		

The following discussion reviews the data inputs and their calculation.

3.3.2 Nodes$_1$

The first grouping of nodes are defined as those that comprise the sites to be served by the waste heat available.

Sink Clusters

Total annual demand for the clusters is determined in Phase I using the coarse or fine-grain method described in section 3.2.1. The latitude and longitude coordinates for the clusters are established using a GIS.

The degree-hours equation in section 3.2.1 is used for determining heat demand of the clusters. Whereas the method is intended for DHS planning purposes, peak demand of individual buildings of the jurisdiction is too specific for the analysis. As such, Phase I of the analysis predicts peak demand of the cluster based on building types and floor areas, accounting for the number of storeys.

For buildings in a cluster with widely differing heat demand profiles, a more detailed analysis is required.

Cluster peak demand can be determined using equation 9.

$$PD_c = \sum_c (UP_b \times A) \tag{9}$$

where: PD_c = peak demand for the cluster (MW)
Σ_c = all buildings of a type in cluster
UP_b = unit peak by building type (W/m^2)
A = floor area for individual buildings

For a more detailed discussion of generalized equations for district heating loads and temperature dependent heat loads according to reference years, (Latosov and Siirde 2010) can be consulted.

Values of cluster peak demand can account for diversity factors. These include the influence of energy efficiency measures, such as installing building insulation, with examples of subsequent reductions listed in Table 6. The improvement factor is based on such parameters as insulation type, local climate, and building vintage.

Table 6. Peak demand improvement factors from using insulation in Ontario buildings (OME 1976)

Cluster Buildings Type	**Improvement Factor*** (%)
Low Density Residential	46
Medium Density Residential	61
High Density Residential	62
Secondary Commercial	62
Industrial	31

* Based on building heat demand (W/m^2).

Also, as this peak demand does not forecast future development in or around the cluster, a development factor can be included as a diversity factor. This factor can use indices associated with the jurisdiction's, or cluster's, allowable development rate. Coverage ratios such as floor area ratios can give an indication of the cluster's future development.

A person familiar with the area's historical growth can therefore make a reasonable estimation, as to the development factor and calculate the growth as a product of future building footprints (e.g. based on floor area ratio) and building type unit peak.

Thermal Stores

Ideally, peak demand periods coincide with waste heat availability. In reality, the waste heat sources are available at times converse to peak residential energy demand.

Much in the same way solar hydronic systems must accommodate this opposite relationship, thermal diurnal stores must be integrated into the DHS. In this method, it is assumed that such stores are situated at the substation for each cluster in the primary distribution network.

Thermal storage capacity for sensible heat in a DHS network can be calculated using the following equation, related to the source hub for energy content, and a function of the temperature change, as shown in equation 10.

$$E = m \int_{T_2}^{T_1} cp_P dT \tag{10}$$

where: E = the amount of energy stored (MW)
m = the mass of the store (kg)
cp_P = specific heat at constant pressure (kJ/kg•°C)
T_1 = lower temperature (°C)
T_2 = upper temperature (°C)
dT = temperature differential (°C)

To actually determine the volume or mass of the store, depending on the type used, for a pre-determined quantity of energy, using equation 11.

$$Q_s = V \times \rho \times cp \times \Delta T \tag{11}$$

where: Q_s = storage capacity (kJ/h)
V = volume of store (l)
ρ = density of liquid in store (kg/m^3; between 958 and 1000 for hot water depending on temperature)
cp = specific heat (kJ/kg•°C)
T_m = T_{max}-T_{min} or highest temperature differential between maximum and minimum temperatures of the store media (°C)

3.3.3 Nodes$_2$

The second grouping of nodes are defined as those that comprise the actual distribution network serving the DHS demand. They are categorized further into three distinct types, described below.

Source Hubs

Data parameters for sources depend on those identified in Phase I of the analysis for the jurisdiction.

The energy medium from the sources is assumed to be hot water, and the supply pressure can vary depending on the process. Hot water production by the waste heat source can be calculated according to equation 12.

$$Q_w = (3600q) \times cp \times dT \qquad 12$$

where:
Q_w = heat content (kJ/hr) = × 2.78 × 10^{-7} (MW)
q = flow rate of refuse water (L/s)
cp = specific heat (4.18 kJ/kg•°C for water)
dT = temperature differential between discharge from feedwater to source node (°C)

Unlike most other approaches to DHS modeling, the source loads are pre-defined with their sizing not being based upon peak demand of clusters being served by the network (Arkay and Blais 1996).

Along with source and sink nodes are intermediate nodes representing transshipment points for the district heat. They are given the same nomenclature and symbols as nodes_2, however, are then assigned a value of '0' to reflect that they have no supply or demand. These nodes are treated as sites of potential but undeveloped or undefined supply, such as geothermal heat pumps discussed further in section 3.3.3.

Heat Upgrading Technology

While the base load in a typical DHS network is typically a CHP plant or biomass facility (NRCan 2009), the peak load energy mix for this method is comprised of process heat from a range of industries.

The low-grade or very-low-grade waste heat sources can be upgraded to a useable temperature with the assistance of boilers and heat pump technology.

Heat pump technologies in the market are typically classified as thermoacoustic, chemical, mechanical, and solar-assisted. The performance of a heat pump, expressed as the coefficient of performance is defined by equation 13 (Cengel and Boles 2008).

$$COP_{HP} = Q_H / W_{net,in} = 1 / (1 - \mathrm{Q_L}/\mathrm{Q_H}) \tag{13}$$

where:
COP_{HP} = coefficient of performance for the heat pump
Q_H = heat rejected at temperature $\mathrm{T_H}$ (MW)
$W_{net,in}$ = net work input or power consumed (kJ/h)
Q_L = heat removed from outdoor $\mathrm{T_L}$ (MW)

It should be noted that limitations exist among all the individual technologies given the condition, form, and quality of the waste stream. Table 7 describes these for a Rankine-driven heat pump.

Table 7. Technological limitations of Rankine-driven heat pump using waste stream heat source (Lokuch 1980)

Waste stream limitations		
Type	Liquid	Vapor exhaust
$\mathbf{T_{min}}$ (°F)	180.0	174.0
$\mathbf{T_{max}}$ (°F)	280.0	254.0
$\mathbf{P_{min}}$ (psia)	15.0	6.4
$\mathbf{P_{max}}$ (psia)	150.0	30.0
$\mathbf{Q_{min}}$ (lbm/hr)	1.5 x 10^5	1.5 x 10^3
End-use stream limitations		
Type	Heating	Space heating
$\mathbf{T_{max}}$ (°F)	300.0	
$\mathbf{Q_{min}}$ (BTU/hr)	3.0 x 10^5	

3.3.4 Distribution Network

The map is transformed into a network, by treating the spatial interactions between node types into an origin-destination pair. As a matrix, for example, this results in rows containing the locations of origin for every pair, and columns containing the locations of destinations for every pair (Rodrigue, Comtois and Slack 2009). The total sum of rows and columns is directly equivalent to the total outputs and inputs, respectively. This conversion, referred to as an OD matrix, reflects the node coordinates and arc locations within the network.

The distribution network of the DHS is an indirect system, a single commodity network, comprised of subterranean hot water pipelines in a closed circuit with heat upgrade and distributed heat exchange grids. The transmission network has three distinct components:

1. Supply and return primary pipelines connecting the modular district grids or neighborhoods to the waste heat process through a central grid.
2. Optional heat pump technology to upgrade the waste heat sources.
3. Modular district or 'cluster' substations, with optional stores, connected to a secondary network that transfers the heat to the buildings.

The heat supplied from the waste heat source to the end-use clusters can be calculated using equation 14.

$$Q_i + W_p + W_{HP} = Q_{loss} + Q_c \tag{14}$$

where:
Q_i = Heat transfer to the water by the waste heat source (kJ)
W_p = Work of the pump in the circulation of hot water through the pipeline distribution network (kJ)
W_{HP} = Work of the hat pump to upgrade waste heat temperature (kJ)
Q_{loss} = Heat losses of the pipeline distribution network (kJ)
Q_c = Heat provided to the end-use cluster substation (kJ)

DHS Pipe Network Sizing

The method assumes a buried channel design for the DHS to ensure a route is available between heat source and sink. Relying on sewer systems or above-ground pipelines may result in restricted routes and difficulty in assessing heat losses associated with pathways.

Heat losses to consider from pipelines can be calculated by using the equation in Appendix 3 for a two-pipe system with insulated pipe in a buried channel (Comakli, Yuksel and Comakli 2003, ASHRAE 2000). The method requires that the user define the values of conditions affecting the DHS network –including the thermal resistance of the soil and daily average outdoor temperature- to properly size the pipe, its losses, and costs.

The method considers the DHS consumer interconnections as an indirect connection; the heat transfer of the modular district grid between the primary system and the secondary system, is assumed to be a shell-and-tube heat exchanger. Figure 13 illustrates the layout of an indirect hot water system, not including control valves and system sensors.

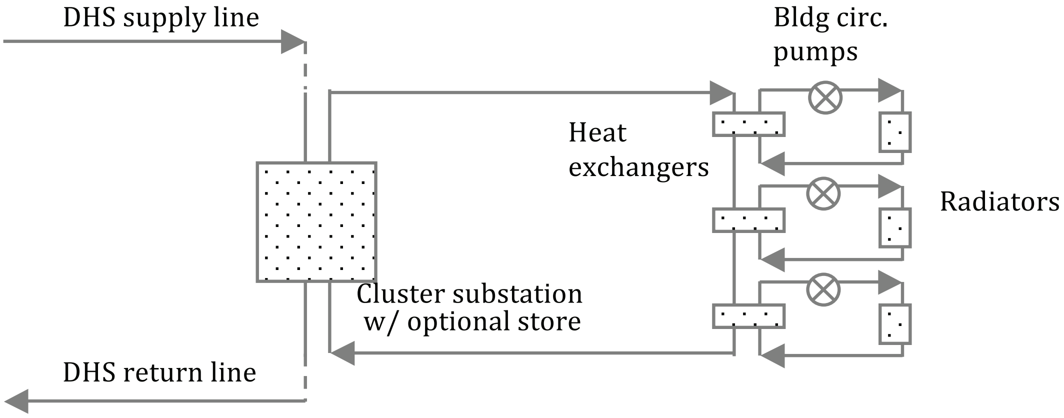


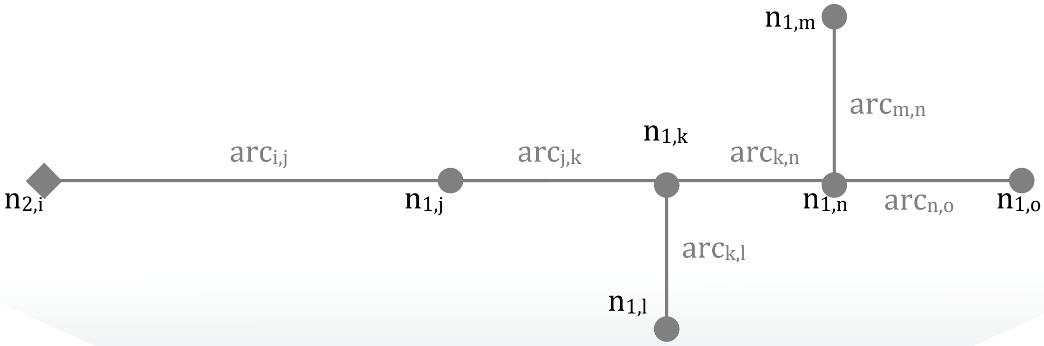
Figure 13. Relationship between primary and secondary system of DHS

The method, however is concerned with network optimizing the DHS cost based on routing to the clusters with high thermal density. By calculating the heat demand for each cluster, at individual nodes$_1$, we can determine the hot water supply along the arcs required to meet the cluster's thermal needs using equation 15 (NRCan 2010).

$$q_c = H_c \Big/ (\Delta T \times c_p \times \rho) \qquad 15$$

where:
q_c = volumetric flow rate of hot water for cluster (m^3/h)
H_c = heat demand for cluster (MW)
ΔT = temperature differential in cluster substation (°C)
c_p = specific heat of water (4.19 kJ/[kg°C])
ρ = density of water (1 kg/m^3)

With respect to two sequential arcs (i,j) and (j,k), for example, the flow rate summation must be calculated for the nodes$_1$ along the primary network ensuring that the last node (i.e. the cluster with the lowest heat demand profile) has its SH and DHW needs met. Figure 14 illustrates this in a diagram with a single node$_2$ and multiple node$_1$ clusters, comprised of the grouped buildings to be served:



Node Type Sinks: n_1 Sources: n_2	Demand (L/s)		Network arcs	Distribution (L/s)
$n_{2,i}$	NA		$arc_{i,j}$	1050
$n_{1,j}$	300		$arc_{k,l}$	200
$n_{1,k}$	250		$arc_{m,n}$	150
$n_{1,l}$	200		$arc_{j,k}$	750
$n_{1,m}$	150		$arc_{n,o}$	50
$n_{1,n}$	100		$arc_{k,n}$	300
$n_{1,o}$	50		—	—

Figure 14. DHS network with one source and multiple sinks

In the waste heat source $n_{2,i}$ has enough process heat to supply all clusters along the DHS network, as seen by the flow along $arc_{i,j}$, with 1050 L/s. In other words, it is a balanced problem as the network ships the exact amount required from the original source nodes to each of the sink nodes. Assuming every cluster has a required heat demand difference of 50 units, beginning with the $n_{1,o}$, the table above shows a cascading approach to a DHS network.

As mentioned previously, the source has a fixed supply pressure. In selecting pipes for the distribution network, their size must accommodate the pressure drop and velocity of the required loads. The pressure drop for steel pipes can be calculated with equation 16 (Rohsenhow, Hartnett and Ganić 1985).

$$\Delta p = \frac{[\lambda(l/d_h)] \times [(\rho \times v^2)/2]}{1 \times 10^3} \qquad 16$$

where:
Δp = pressure loss (kPa)
l = length of hot water pipe (m)
d_h = hydraulic diameter (m)
ρ = density (kg/m^3)
v = velocity (m/s)
λ = friction coefficient
[can be determined by Moody diagram; consult (Rohsenhow, Hartnett and Ganić 1985)]

Calculating the head loss of the pipe network can further reflect energy loss (i.e. foot pounds of energy per pound of distribution fluid), exclusive of temperature change. Pressure drop on the basis of energy per unit volume necessitates adjusting temperature for the volume differences when combining supply and return lines (ASHRAE 1972). Equation 17 calculates unit head loss, accounting for pumping head and pipe pressure drop.

$$h = (3.9/d^{1.26}) \times (V/0.30448)^{1.95/d^{0.018}} \qquad 17$$

where:
h = unit head loss (kPa/m)
d = internal diameter (mm)
V = velocity (m/s) = $1273Q/d^2$
Q = hot water demand (L/s)

The pressure drop constraint can determine the proper selection of pipe diameter. The constraint dictates that head loss must be less than the fraction produced by the pressure difference between the upstream and designated minimum load point, and the length of pipe from the upstream end-point to the load point most distant in the network, as shown in equation 18 (Morofsky and Verma 1979).

$$h \leq (P_{up} - P_{min}) / D_{max} \qquad 18$$

In the event that the unit head loss does not comply with this constraint, a larger diameter pipe is selected for the hot water network.

To apply this framework to more than one source requires that the arcs between nodes_2 are sized for the available loads, not just the node_1 cluster demands. Equation 19 provides an iterative flow balancing procedure developed by (Morofsky and Verma 1979) to establish the delivery pressures and load distribution associated to each plant.

$$\varepsilon = (n\Sigma Q_i) / [\Sigma(Q_i/\Delta P_i)] \qquad 19$$

where:
ε = iterative correction added to pressure (kPa)
n = exponent in relationship $\Delta P = (\text{constant})(Q^n)$
$Q_{i\ldots}$ = flow rate to meet demand at each node extending from nodes_1 between two nodes_2 (L/s)
$\Delta P_{i\ldots}$ = pressure drop at each node extending from nodes_1 between two nodes_2 (kPa)

DHS Network Design

A basic minimum-cost flow modeling approach can be used to design the DHS primary network. The method determines the path of the network by assigning traversal cost a_{ij} to the arcs. These arcs are directed and have capacities based on the DHS piping, with the cost being directly proportional to the amount of flow. Each arc's path of flow is specified by the direction of its arrowhead, and the maximum amount of flow for each arc is indicated by its stated capacity.

The major nodes comprising the network, described as nodes_1 and nodes_2, have been identified. The remaining nodes of the network route are transshipment nodes.

A network, for which the preliminary design uses the minimum cost flow modeling approach, assumes the objective function and constraints listed in equation 19 (Hillier and Lieberman 2010) for the flow in $a_{i,j}$.

$$\textit{minimize:} \qquad Z = \sum_{i=1}^{n}\sum_{j=1}^{n} c_{i,j} x_{i,j} \tag{19}$$

$$\textit{subject to:} \quad \sum_{j=1}^{n} x_{i,j} - \sum_{j=1}^{n} x_{j,i} = b_i \qquad \textit{for each node i (flow conservation)}$$

$$\sum_{j=1}^{j=n} x_{i,j} \le s_i \qquad \textit{supply constraints (i = 1, 2, ... m)}$$

$$\sum_{i=1}^{i=m} x_{i,j} \ge d_j \qquad \textit{demand constraint (j = 1, 2, ... n)}$$

$$0 \le x_{i,j} \le u_{i,j} \qquad \textit{for each } a_{i,j} \textit{ (capacity and non-negativity constraints)}$$

where:
Z = cost of flow
$c_{i,j}$ = cost of arc i→j
$x_{i,j}$ = flow through arc i→j

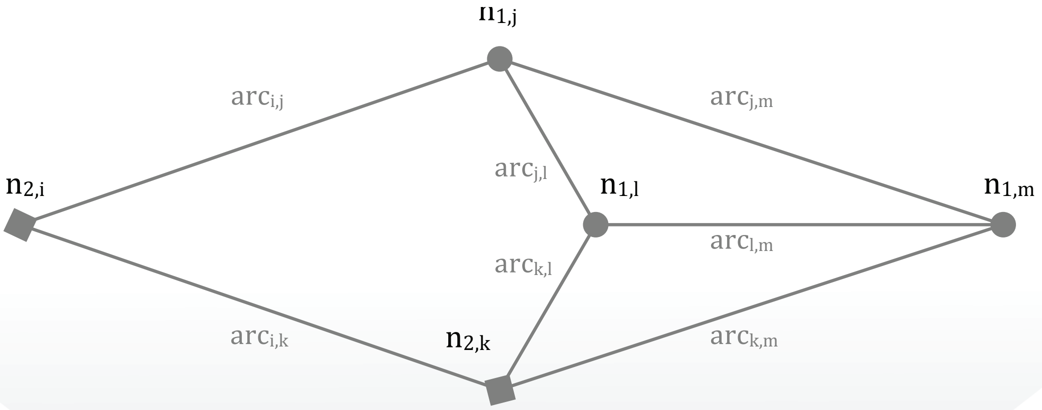
Within linear programming theory, the first formulaic line above describes the objective function while the second and third line describes its set of constraints. In combination, these are known as the problem's formulation (Bertsekas 1998).

The preliminary network has sufficient capacity to facilitate the distribution of all the flow generated at nodes_2 (i.e. sources) to satisfy the demands of nodes_1. The objective function, then, is to minimize the total cost of piping, storing, and upgrading the available supply as it meets these demand sinks.

The total cost is then compared to removing individual demands at nodes_1, such as those consumers, with the largest heat demand or those furthest away from nodes_2-sources in the jurisdiction. In this sense, the method has an adaptive routing capability, whereby a change in user-input conditions of the network can affect the path of the DHS route.

These results can be compared to costs for compartmentalizing the DHS by serving individual sources with sinks. This can be achieved by sizing the system for all nodes of interest and calculating the energy flow, losses, and costs along each arc of the jurisdiction; for example, using street length.

Figure 15 shows a network with two sources, two sinks, and a single transshipment node.



Node Type Sinks: n_1 Sources: n_2	Heat loads (kW)		Network arcs	Costs
$n_{2,i}$	450		$\text{arc}_{i,j}$	20
$n_{1,j}$	0		$\text{arc}_{k,l}$	8
$n_{2,k}$	250		$\text{arc}_{k,m}$	20
$n_{1,l}$	-800		$\text{arc}_{j,l}$	8
$n_{1,m}$	-600		$\text{arc}_{i,k}$	20
—	—		$\text{arc}_{l,m}$	15
—	—		$\text{arc}_{j,m}$	20

Figure 15. Single-commodity network with multiple sources, multiple sinks, and transshipment node

In contrast to Figure 14 where flow rate is described, Figure 15 lists the cost of flow associated with each arc along the network. Also, it lists the loads supplied or required at each node by signifying supply with positive values, demands with negative values, and transshipment nodes with values of zero.

Similar to what might be expected of a DHS network based on waste heat as a primary fuel type, the total demand will not always match the available supply. This represents an unbalanced problem, meaning ‘dummy’ nodes must be included in the network.

If total supply is less than total demand, certain demand nodes or buildings within the cluster will have to be excluded from the analysis. With such unbalanced systems, a dummy supply point is included as a penalty associated with excess demand; this is achieved by adding a new node with a value representing the difference.

3.4 Fuel Savings and GHG Emissions

To calculate fuel savings for a cluster connected to the DHS network, it is necessary to determine the mix of heating fuels the cluster uses. The total fuel savings are equal to the amount of each fuel saved (as a percentage of the total fuel mix), as a function of the average seasonal efficiency of the heating system, the calorific value of the fuel, the energy demand of the cluster.

For a cluster using exclusively natural gas and served in whole by the proposed DHS, for example, the fuel savings would be calculated using equation 20.

$$F_{NG} = T_{NG}\left[[Q_{cl}\,(1 - \eta_{HS})] + Q_{cl}/Q_{NG}\right] \qquad 20$$

where: F_{NG} = amount of natural gas saved (m^3)
T_{NG} = percent of cluster buildings using natural gas as primary SH/DHW fuel type in the cluster (%)
Q_{cl} = Energy demand of cluster (kWh)
η_{HS} = seasonal efficiency of heating system (%)
Q_{NG} = calorific value of natural gas (kWh/m^3)
Therefore the cluster's $F_{total} = F_{NG}, F_{LFO} \ldots F_{HFO}$

3.5 Discussion on Calculations

The figure in Appendix 4 is a representation of the method's flowchart, including the steps for both phases described in this chapter.

Further discussion on the calculations associated with the steps is available through the sources previously cited as well as by consulting (NRCan 2009) and (NRCan 2010) for calculating heat load and energy use of buildings; (Towler and Sinnott 2008) for pipe network sizing and losses; (Bertsekas 1998), (Winston and Venkataramanan 2003), and (Patterson and Harmel 2001) for network optimization and linear programming algorithms; (Reisman 1986) for district heating network modeling; and (Stillwell and Clarke 2004) for applied GIS and spatial analysis.

3.6 Summary

This chapter described a method for identifying waste heat sources and potential sinks and developing a preliminary design for a DHS primary network to connect the sources and sinks. The equations required by the method were included as part of the discussion.

CHAPTER 4 : IMPLEMENTATION AND RESULTS

The following chapter discusses the implementation of the method described in Chapter 3. A case study using the implementation is also presented.

4.1 Implementation

The method is implemented using a combination of two Windows programs, ArcGis and Microsoft Excel, for the identification and preliminary network design components, respectively.

In the identification components, a GIS geodatabase—a collection of geographic datasets with defined typologies—is created in ArcGIS 9.3 software with two shape files. These shape files represent street layers and building layers for the jurisdiction, described as lines and polygons, respectively, in GIS terminology. These can be sourced from most municipal GIS data storage centre. The jurisdiction is 'clipped', according to the user-defined boundaries.

Thermal remote sensing imagery for thermal band 6, taken at 30-60m from the earth's surface by the Landsat 7 satellite, acquired from a USGS (United States Geological Survey) data provider. The orthorectified imagery contains individual pixel values that correspond to table cell value for use in Excel. They are then converted to spectral radiance and subsequently calibrated to surface temperature before finally being re-inserted as a raster layer into the ArcGIS geodatabase. This gives the user a starting point for which sites to investigate further for waste heat from industrial and commercial facilities.

Land-use data, which can be normalized according to population distribution, is sourced for the jurisdiction. Such data should be categorized by parcels of land as small as possible, such as census tracts or dissemination areas, in order to group buildings together to form clusters. An attribute table, a tabular file with columns and rows representing a class of geographic features for spatial coordinates of a layer, is generated by ArcGIS for the feature class. Data on the number (or proportion per building total) of buildings, categorized according to the building types defined by the user, as well as the footprint and number of storeys are entered in the attribute table for the land-use feature class. The footprint, or surface area, can be recorded based on the building polygon layer shape file.

Next, the fuel types for primary heating systems of each building are recorded and entered into the attribute table. The proportions of fuel types used in cluster buildings are calculated and generic heating system efficiencies are considered to determine total amount of each fuel consumed for the entire cluster.

Data can be input for each model building into energy simulation software such as HOT3000 (NRCan 2009) for residential buildings, ENERPASS (UDE 2010) for small commercial buildings, and DOE-2/BLAST or EnergyPlus (Crawley, et al. 1999) for large commercial and institutional buildings. If such data is unavailable, or if the user prefers a simplified analysis, the graphical interface allows default values to be used. Once all the model buildings have been simulated, technical reports on energy use are produced. The flowchart in Appendix 2 illustrates the method.

Unless the SH and DHW loads for each building of the parcels is calculated, indices are developed based on averages. An energy intensity factor, an index of energy used for an area (e.g. W/m^2), can be calculated for the average of each building type. The energy intensity of the buildings is included in the attribute table. At this point, the user can decide to calculate the heat load profile for a cluster of common building types, or the parcel as a total to be served by the DHS.

The cluster or ‘hot-spot’ analysis geo-processing tool, obtained from local statistics, is then applied to the values in ArcMap. Each of the sink cluster’s substations can be situated at an arbitrarily selected point in the middle of the cluster. Alternatively, for increased precision, a point feature class can be created to represent all the building polygons of the selected cluster and the ArcMap midpoint tool used to create a new vertex or point for the substation. This, then, represents the type nodes1, or sink nodes.

Next, using the sketch tool of ArcMap, point features are added as a shape layer file with *x,y* coordinates for the location of each potential heat source. The attribute tables associated with each of the point features are then populated with values describing characteristics of the heat source including its media of rejection, temperature, flow rate, and heat load. Such data can only be accurately determined with energy audits, metering, or both for the point features' sites.

The point features can also be set to a multipoint feature class if the user wishes to reflect both commercial and industrial waste heat sources, for example, as a single node type nodes2.

The network analyst geo-processing tool is used to develop an OD matrix creating a network of nodes and arcs from each street and intersection, respectively. Route analysis is then performed in ArcGIS on the network to determine the shortest path between each of the nodes, type nodes1 and nodes2, along all the nodes of the network.

The network uses a *true shape* output type with sequenced points, to follow street edges, and one-way restrictions applied to the analytical settings. While each node along the network can be considered a transshipment node, the implementation considers these as hypothetical sites assigned with distances relative to those between each nodes1 and nodes2.

The method's design component uses Excel to pair a DHS system-sizing module with a linear programming module, based on user inputs, to produce the network layout.

With the path distances between all nodes established, the data is exported from ArcGIS and imported into Excel as a *csv* file.

First, the system-sizing module is executed with load supply and demand data for the node1 clusters and node2 hubs. This determines, based on the formulas described in Chapter 3, the diameter of the pipe as a function of volumetric flow rate needed, implemented as Excel cell-expressions. The losses and costs of the system are then calculated in the Excel cells, as well, as a function of the pipe length.

Next, the linear programming module determines the sequence for the DHS based on the objective function described in section 3.3.4. This module uses equation 19 implemented as Excel cell-expressions. Further constraints or other parameters, such as temperature, can be applied to the algorithm to produce a network sequence based on a multi-objective function.

Again, as the DHS will likely represent an unbalanced system, a 'dummy' supply node can be added to balance the problem with the arc cost from this node to each cluster reflecting the costs of unmet demand. These nodes can then also be considered for heat upgrade.

The Excel *Solver* plug-in or *Visual Basic* programming environment can be used to calculate iterations of the objective function based on Excel cell-expressions of the objective function and constraints. Excel *Solver* was used in this implementation.

Once the sequence is determined for the objective function, the total costs for the DHS network is determined based on the sum of all pipe costs in the network. The diurnal thermal storage used for each cluster can be determined using equations 10 and 11, with the cost per litre of required storage calculated for each cluster.

The potential fuel savings for the cluster as a result of implementing the optimized DHS are then calculated in Excel, by accounting for the fuel type mix of the individual clusters.

With the fuel savings determined, GHG emission savings, by individual greenhouse gases or in carbon dioxide equivalents, are calculated using fuel emission factors. These factors are the ratio of GHG's generated by a specific quantity of fuel (EIA 2010). The major GHG's considered are carbon dioxide, methane, and nitrous oxide.

Total transmission and distribution losses associated with the DHS are calculated with an indices determined per metre of pipe, with equations 14 to 19 and the equation in Appendix 2.

The resulting preliminary network design is formatted as a *SourceDataset* table to be exported back into ArcGIS as an event table, a GIS tabular data source with geographic coordinates for the purpose of developing spatial datasets. With the x,y coordinates for the nodes_1 and nodes_2 types, respectively. Object ID's are assigned by ArcGIS and names are added as single character subscripts (e.g., k, l, m). For a more efficient output, a cross-referenced database between Excel and ArcGIS with field mapping to allow for updating values in the source field could be developed; in the case of this implementation, the values were manually input. This highlights the sequencing (i.e. specific source-sink connections) of the preliminary network feature class as soon as the linear programming module has generated its results.

Of note, the proposed method is also conducive to using software packages supportive of large-scale linear programming and mixed integer programming. Excel has been used for a simplified representation and investigation of the method's potential. The implementation can be further developed by pairing programming language with the GIS software.

Table 8 lists some of the associated assumptions, in abbreviated form, for the implementation and subsequent case study.

Table 8. Assumptions of Implementation and Case Study

Parameter	Assumption	Reason
System Boundaries	Geographical system boundaries are based on socioeconomic similarities, high-density development, and mixed-use building form.	Such features are linked with higher thermal density and opportunities for cross-optimization of energy potentials, as discussed in Chapter 2.
Time Growth	Pipe over-sizing factor, a projected growth variable, is built into the design module of the method.	To account for temporal growth of the DHS from further urban development.
Economic Analysis	Fuel costs to individual consumers of clusters served by DHS primary network not determined.	Dependent on costs associated with DHS secondary network, system financing, and ownership.
Thermal Storage	Optional stores can be situated at the cluster substations or in the individual buildings; no further cost analysis on stores is included.	Storage design must include a comprehensive assessment of type, capacity, flexibility, cost parameters; part of secondary network.
Primary and Secondary Network Heat Transfer	System costs or transmission losses associated with heat exchangers at the supply or sink-side are not considered.	These are dependent on a range of heat exchanger types, as well as detailed data on parameters for the media of rejection.
System Design	Fiberglass insulation is used with a thermal conductivity of 0.65 W/mK. Average outdoor temperatures, T_{ex}, corresponding to uninterrupted average soil temperatures, used for design of the DHS piping network.	Based on literature sources (ASHRAE 2000) and (NRCan 2010).
Cluster Heat Transfer	Design of lateral pipelines between buildings of clusters are not considered.	These constitute secondary network components, beyond the scope of the DHS primary network.

A further discussion on these and other assumptions is available in Appendix 1.

4.2 Case Study

To simulate the model with actual datasets for a high-density, mixed-use jurisdiction, North End Halifax has been chosen. The jurisdiction has been chosen given its high-density development, mixed-use neighborhoods, and proximity to industrial processes.

Where data is unavailable or its detailed collection unfeasible given the scope of this research, assumptions have been made. A discussion of these can be found at the end of this section.

4.2.1 Overview

Halifax Regional Municipality, HRM, is the capital of the province of Nova Scotia and is the largest metropolitan area in Atlantic Canada and the thirteenth largest in Canada (HRM 2007).

The HRM has as its objectives for regional planning to "promote the use of alternative energy generation and distribution (e.g. … district heating)," as well as to "define and cluster communities to … decrease per-capita cost of investment, operations, lifecycle and energy consumption for infrastructure and facilities" (HRM 2004).

The jurisdiction under consideration is North End Halifax, a distinct socio-economic region in the Northern half of Halifax's peninsula, central HRM. As the most densely populated part of HRM (StatsCan 2002), its perimeters are delineated in Figure 16.

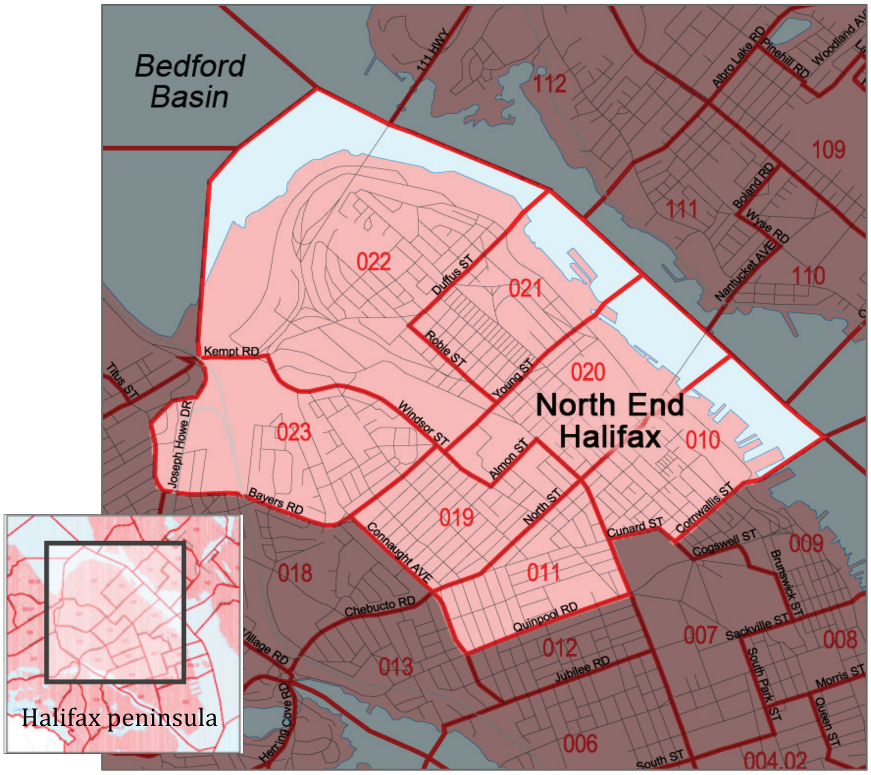


Figure 16. Map of North End Halifax (StatsCan 2002)

The case study examines an area defined by the municipality as Districts 11 and 14 (HRM 2010) and framed by the Bedford Basin to the North; by the Halifax Harbour to the East; by Cornwallis Street, Cunard Street, and Quinpool Street to the South; and by Connaught Street, Bayers Road and Joseph Howe Drive to the East.

The bordered and numbered areas correspond to census tracts of this jurisdiction. These tracts can be further examined to reveal energy-use trends and building typology.

4.2.2 Phase I : Spatial Layer

In the first phase, waste heat sources and thermal density sinks are identified for the jurisdiction.

A GIS geodatabase is established with two shape files representing street layers and building layers for the clipped jurisdiction, with geospatial data sourced from (GISC 2010, DMTI 2010, SNS 2009).

DHS Sources

Thermal remote sensing imagery is downloaded for the jurisdiction through GeoBase, “a federal, provincial, and territorial government initiative that provides quality geospatial data for all of Canada” (CCOG 2010). The orthorectified imagery is then calibrated to surface temperature. As shown in Figure 17, this raster layer, superimposed upon the shape layers for the jurisdiction, can reveal temperature anomalies in the urban landscape.

Access to these raster layers is, unfortunately, only available for time series over yearly spans, not hourly. However, such a map offers an initial clue to potential heat sources that can then be investigated further.

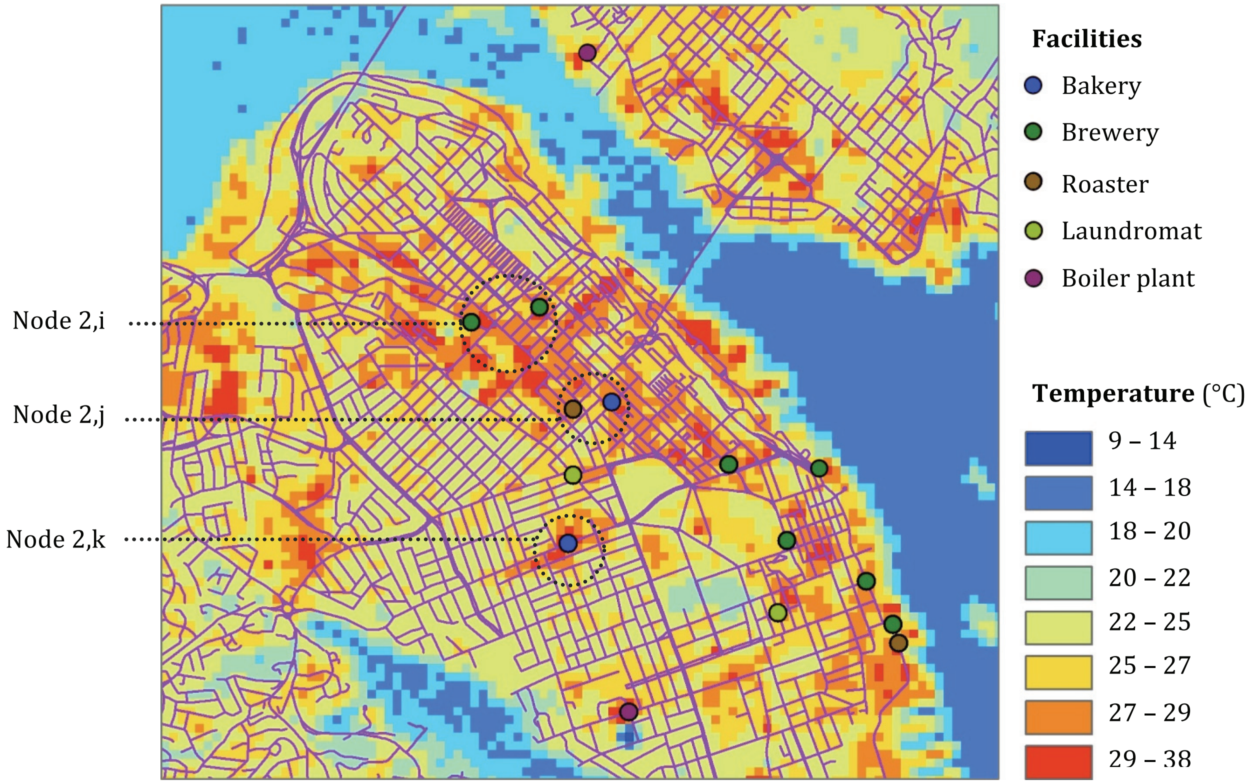


Figure 17. Thermal map for Halifax peninsula (Landsat-7 2003)

Waste-heat hubs, nodes2, are shown where facility locations and temperature hotspots appear to coincide.

Municipal wastewater services were contacted to establish the temperature, pressure and flow rate of water discharged from the facilities. Unfortunately, such data was either not readily available, confidential, or both (Sibbald 2011). In HRM, all water must have set limits of pH levels and temperature (HRM, By-Law W-101: Respecting discharge into public sewer 2003), implying that industry must purge and cool discharge from their facilities before entering the wastewater system.

Therefore, to simplify the model input datasets, it is assumed that heat exchangers and direct supply points from the source facilities result in supply temperatures of 120°C for the waste streams.

Figure 17, in combination with a data collection survey of the actual jurisdiction, results in three commercial and industrial waste hubs being identified for their waste heat potential. These waste heat hubs, and their characteristics, are represented in Table 9 with their associated size.

Table 9. Hypothetical supply loads of hubs for jurisdiction

Nodes2 IDs	Waste Sources	Heat Supply Load (kW)
2,i	Industrial Brewery Commercial Brewery	1500
2,j	Commercial Laundromat Commercial Roaster Commercial Bakery	1000
2,k	Commercial Bakery Commercial Kiln	550

As figures are not available for the specific process heat, engineering assumptions based on statistical averages, processing efficiencies, and other case studies were used to estimate hourly heat supply loads.

For example, using vapor recompression in its wort boiling processes, it can be determined that Oland's brewery in Halifax could potentially produce 5400 MWh of thermal energy per year (Galitsky 2001) based on a production capacity of 1.2 hectolitres (FPD 2002). Indices of energy efficiency are available (as discussed in Chapter 2) to determine potential heat supply loads however, at present and largely for proprietary reasons, no comprehensive energy use database exists for energy flows specific to the Canadian brewing industry, by facility or by region (Gregory 2011).

Data tables in Chapter 2 and 3 provide examples of some facilities and process heat availability. Performance data produced through energy assessments and material balance of individual facilities can provide a more detailed estimate of losses with potential supply loads.

DHS Sinks

Establishing heating profiles for individual buildings involves compiling data on parameters including building envelope, orientation, height, and occupant behavioral patterns.

As the model serves to give an overview of heating needs for clusters of several buildings, an index, based on wattage per square metre, is developed according to building vintage and storeys. An average is then taken to classify the building type based on its insulation.

The buildings examined for the sink clusters of the case study have been categorized into three types: residential, commercial, and institutional. Using the residential building type as an example, building space heating and domestic hot water load intensities are calculated, for

Table 10.

Table 10. Building loads according to storeys and vintage (NRCan 2010)

Storeys	Vintage	Average main floor area (m^2)	Bldg SH avg load intensity (W/m^2)	Bldg DHW avg load intensity (W/m^2)
1	Pre-1941	87.7	71.3	13.7
	1941-1960	85.4	76.7	10.5
	1961-1978	103.7	62.2	11.6
	1978-1993	117.1	55.1	10.3
	Post-1993	106.5	43.2	11.3
1.5	Pre-1941	110.6	90.5	10.9
	1941-1960	75.1	104.6	16.0
	1961-1978	119.5	71.6	10.0
	1978-1993	89.3	75.6	13.4
	Post-1993	88.3	54.4	13.6
2	Pre-1941	92.6	108.0	15.1
	1941-1960	73.4	117.9	19.1
	1961-1978	117.4	83.5	10.2
	1978-1993	98.8	76.9	12.1
	Post-1993	83.1	74.6	16.9

To determine residential building types of interest, tract data can be analyzed for household characteristics by dwelling type, as shown in Figure 18. An initial scan of the chart for total households in the area reveals that the majority of residents, almost 75%, occupy dwelling types in two distinct categories: single-detached houses and apartment buildings (with either fewer than or more than five storeys).

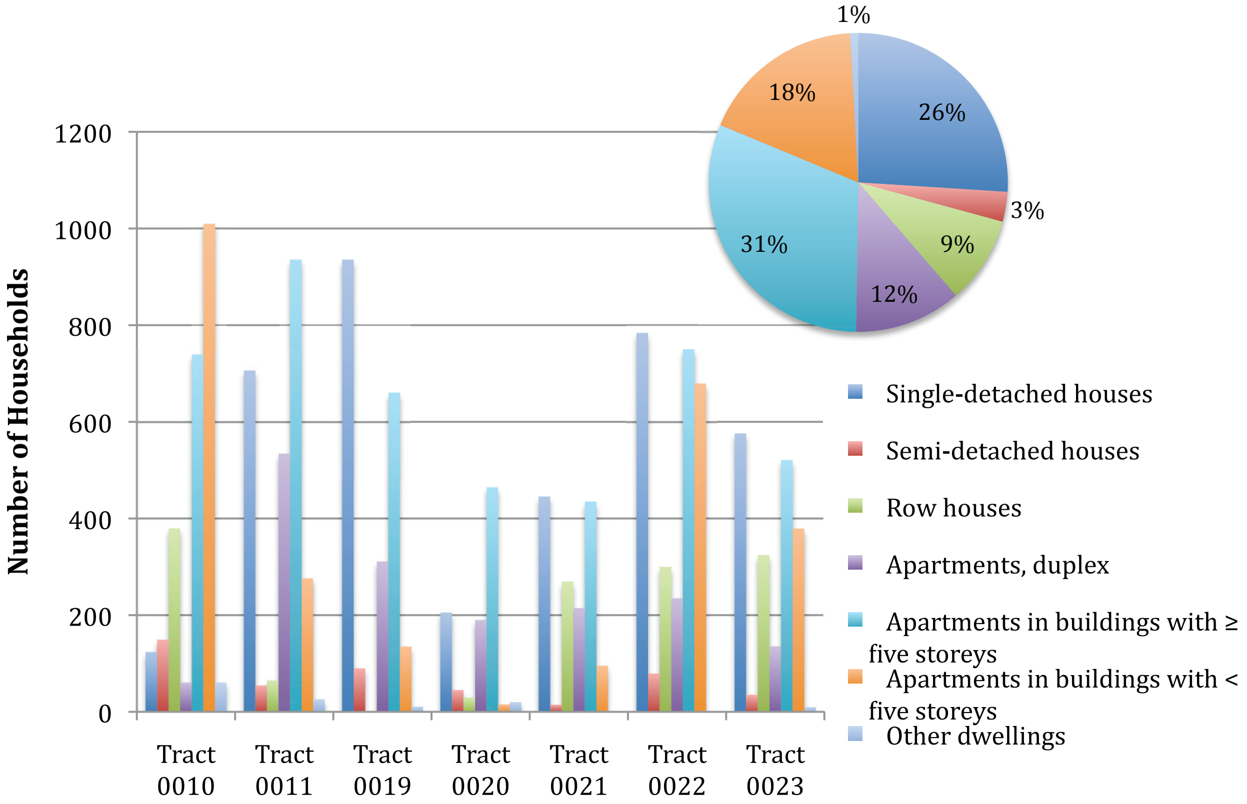


Figure 18. Household types by tract in jurisdiction (StatsCan 2006)

Such data is not available for commercial or institutional buildings in the area without going to municipal land use records or through the property taxes department. In the absence of such data, random selection and site surveys were used to identify non-residential buildings within the jurisdiction for the purpose of conveying the method's implementation.

4.2.3 Hub Layer

With data on number of households by dwelling type for a section (i.e. neighborhood or tract) of the jurisdiction, along with energy indices for the dwelling types, a heat sink cluster map can be generated.

Heat load values for the different building types are based upon a design temperature of -18°C and estimates for the local climate (CANMET 1997, Ciavaglia 2003).* A more detailed inventory of load profiles based on all commercial and institutional types in mixed-use jurisdictions would improve the cluster data.

Figure 19. Cluster analysis for high-density residential heat sinks

The design temperature is used to calculate the heat loads for the building types, for both space heating and hot water, using the load equations in Chapter 3.

The shaded tracts of Figure 19 represent number of residential dwellings normalized according to total population figures while the graduated circles symbolize the average thermal density (W/m^2) for the dissemination areas; these areas represent

---

* Design temperature considers the temperature of the climatically coolest days for the jurisdiction.

subsets of the tracts defined in Figure 18. As might be expected, those areas with proportionally more dwelling figures have increased thermal densities.

However, thermal density is also a function of dwelling type as single detached houses, for example, have statistically higher energy intensities than other dwelling types (NRCan 2009). The energy intensity factor is calculated as a fraction of the total estimated annual energy use and the land area for the tract (Gilmour and Warren 2007).

As illustrated in Table 11, indices for eight types of buildings are established to calculate loads for the clusters identified; peak loads are used to size the heating system, as discussed in Chapter 3. Load averages for DHW in residential units were used for the two other building types.

Table 11. Indices of building heating loads of jurisdiction (CANMET 1997)

		Cluster building type								
Variable	Nom.	RES1	RES2	COM1	COM2	INS1	INS2	INS3	INS4	Units
Bldg peak heat load	$P_{j,tot}$	50	89	40	79	35	74	85	124	W/m^2
Bldg peak SH load	$P_{j,SH}$	40	70	30	60	25	55	75	105	W/m^2
Bldg peak DHW load	$P_{j,DHW}$	10	19	10	19	10	19	10	19	W/m^2
Bldg Type	-	House	House	Retail	Retail	School	School	Hosp.	Hosp.	–
Bldg insul. efficiency	η_I	1	0	1	0	1	0	1	0	1=Good 0=Poor

All buildings were assumed to have 88% insulation coverage, or the amount of insulation for the building envelope, based on residential statistics for Canada (NRCan 2010). Insulation identified as 'good' can refer to board-stock or spray-applied insulation for building envelopes, with R-values of between 4.5 to 6.7 R/in. Conversely, insulation that is poor can represent batt-type or older loose-fill insulation with R-values typically falling between 2.8 and 3.7 (CMHC 2010).

As an example, if a tract is found to have six apartment buildings of four storeys each with a 200m^2 footprint and new insulation, its peak space heating load is estimated at

192kW; a product of these values multiplied by the $P_{j,SH}$ value of for the cluster building type.

With the clusters of high thermal density identified, the polygon features are selected for the building layer shape file (see section 4.2.2) to identify the footprint of individual buildings in the cluster. The actual number of storeys for each building are determined through site visits or by consulting municipal departments for civic and commercial address data. In this case, as such data was not readily accessible (Lowerison 2011), values for these have been assumed for the case study.

The degree-hours calculation, equation 4 in Chapter 3, can be used to determine the heating energy use. The load profile for the proposed system is shown in Figure 20, sorted by hourly space heating and DHW load values for the year (i.e. 8760 hours/annum) in descending order. Typically, these curves can help illustrate the base-load and peak requirements when sizing a system.

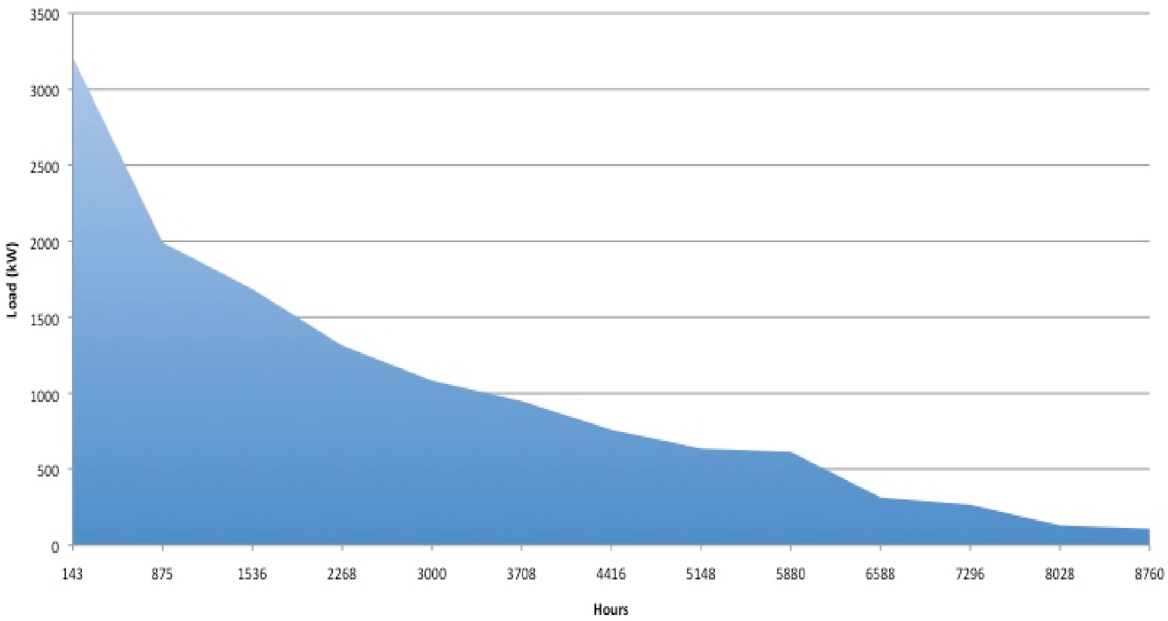


Figure 20. Load duration curve for heat sink clusters of jurisdiction

In the case of the three supply nodes listed in Table 9, capacities have been calculated of 1500 kW, 1000 kW, and 550 kW, respectively. According to Figure 20, the number of operational hours for the sources can be visually determined by identifying where the curve intersects with the load; waste hub *node i* will be expected to operate at practically full capacity for 1,902 hours, with *node j* and *node k* operating at 3,531 hours and 5,920 hours respectively.

The product of the area beneath the curve in Figure 20 and the peak heat load calculated for the clusters corresponds to the thermal energy use of the DHS for the year.

This also represents a scenario where demand exceeds available supply; an occurrence assumed to be typical for optimization of waste heat with cluster demand in high-density areas.

4.2.4 Phase II : Nodes Layer

Ten nodes have been established as the primary network points of interest based on the cluster analysis of Figure 19 and estimates based on Figure 17. In total, the method has identified three source nodes (i.e. type nodes2) designated as $n_{2,i}$, $n_{2,j}$ and $n_{2,k}$; four sink cluster nodes (i.e. type nodes1) designated as $n_{1,l}$, $n_{1,m}$, $n_{1,n}$ and $n_{1,o}$, classified as RES2, COM1, INS1, and RES1, respectively, to reflect building types of the area; and three transshipment nodes designated as $n_{2,p}$, $n_{2,q}$ and $n_{2,r}$.

These are the ten nodes of interest and are referred to as the *main* nodes of the network.

As the proposed DHS in this case study will follow the street plan (i.e. buried pipe along transport infrastructure) to ensure site accessibility (Antonoff 2004), the street layer can be used to establish a network of nodes and arcs. In Figure 21, the nodes are visible as red points while the arcs are green.

It is of critical importance that projected coordinates for the geodatabase layers of the network are synchronized (i.e. each layer is geographically positioned according to every other layer), to ensure accuracy of distance calculations.

Figure 21. Network and shortest distances measured for arc routes

Route analysis is performed by ArcGIS on the network to determine the shortest path between each of the ten main nodes along all the nodes of the network. The network uses a 'true shape' output type with sequenced points, applied to follow street edges, and one-way restrictions selected in the analytical settings.

Where there may exist barriers to the route, though none occur in this scenario, the analysis can avoid certain paths along the network. Figure 21 illustrates the measurements between two pairs of main nodes for sources and sinks in the network, computed in metres.

4.2.5 DHS Network Sizing

To properly size the hot water pipes for the system, the volumetric flow rate is first calculated based on the system's total heat load requirements as well as the density and specific heat of water. These latter parameters are a function of the average fluid temperature of the DHS, and are 962 kg/m^3 and 4,213 J/(kg°C), respectively (Cengel and Boles 2008).

A pipe over-sizing factor of 5% is added to account for possible growth to the DHS demand over time without having to install new pipe. The pipe sizing selection results in a DN (i.e. nominal diameter) selection of 150mm, with a volumetric flow rate of 66 m^3/h. The transmission and distribution costs for the pipe, including the cost of laying the infrastructure and circulating the hot water throughout the system, is $605/metre.

Transmission and distribution losses along the arcs have been calculated as 19 W/m^2 for the pipe size selected. This is a function of the system's average fluid temperature, annual soil temperature, and total thermal resistance of the system components.

The transshipment nodes for the network represent sites where potential supply can come online in the future. These can correspond to ground-source heat pumps, for example, and a site-specific feasibility assessment should be performed for any proposed system. As these nodes do not represent actual sites on the map, they are given an arbitrary distance taken as half of the average distance between each source node (i.e. nodes2) and every other sink node (i.e. nodes1).

Figure 22 shows the network diagram for all possible flows associated with this network.

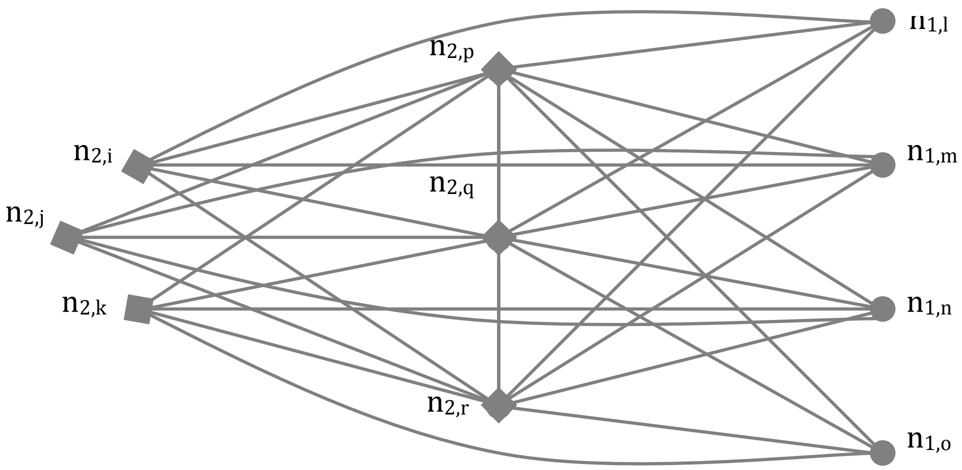


Figure 22. Network diagram of connectivity and potential flows for DHS

The heat sources can flow directly to the sink clusters or through a transshipment node to collect more heat.

In this network, transshipment nodes have been assigned a supply value of zero. Heat upgrade can be considered for the sink node that does not have its full heating load met by the system. If heat upgrade technologies are situated at the transshipment nodes, then, the network can be sized again based on the increased supply.

Determining the storage size for thermal storage is primarily a function of time-of-day use for demand and supply availability. Hourly profiles of load production are not included as part of this model or the overall DHS system and, as illustrated in Figure 6, it is assumed that such storage would be a component of the secondary DHS system. Similarly, the network does not account for heat transfer stations at the source hubs or the sink clusters.

4.2.6 DHS Network Design Formulation

To account for the system's demand exceeding its supply, the formulation algorithm is treated as an unbalanced generalized network flow problem with transshipment points.

A dummy node, an extra imitation source used as a practical substitute, assigned with a value equal to the supply shortfall can balance the problem. By including a dummy node in our formulation, we can now determine the network routing for the preliminary network design.

The linear programming algorithm of its objective function and constraints (i.e. its formulation) is described in equation 19 based on a minimum cost flow problem (Hillier and Lieberman 2010). The function, then, is to minimize system cost with positive integers for the arc flows. The model is subject to the net outflows for each supply node being less than or equal to the available supply, and the net inflow being greater than or equal to the required demand for each demand node.

Similarly, the net inflow must equal the net outflow for each transshipment node, and the arc flow must be within its bounds for each arc. The lower bounds for all arcs are 0 while the upper bounds are the maximum supply available for the network.

Given this data, Table 12 illustrates the resulting sequence of the primary network design with the waste heat loads described for the jurisdiction.

Table 12. Network optimization for DHS case study

Unbal: D>S Shipments	To Clusters							Transshipment Nodes : 🟦			
From Waste	Node *p*	Node *q*	Node *r*	Node *l*	Node *m*	Node *n*	Node *o*	Shipped	Constr.	Supply LOAD (kW)	
Node *i*	0	0	0	900	0	0	600	1500	≤	1500	
Node *j*	1000	0	0	0	0	0	0	1000	≤	1000	
Node *k*	164	0	0	0	260	126	0	550	≤	550	TransNode Supply:
Node *p*	~~1959~~[*]	0	0	1164	0	0	0	3123	≤	3123	0
Node *q*	0	~~3123~~	0	0	0	0	0	3123	≤	3123	0
Node *r*	0	0	~~3123~~	0	0	0	0	3123	≤	3123	0
Node dummy	0	0	0	73	0	0	0	157	≤	73	
Received	3123	3123	3123	2137	260	126	600	TOTAL	Supply:	3050	
Constr.	≥	≥	≥	≥	≥	≥	≥				
LOAD (kW)	3123	3123	3123	2137	260	126	600		Demand:	3123	

The white cells in the central part of the table represent the flows along each arc between the nodes listed in the column and row headers. When the Excel formulation runs, the algorithm changes the cell values producing numerous iterations until the DHS network is found given the objective function and constraints specified.

Based on this preliminary design, the path of the network is determined. Figure 23 shows the final path of the network when re-inserted with the final routing into the GIS software.

---

[*] The cells holding values with a strikethrough simply represent that there is no arc between the same node.

Figure 23. Optimized DHS network for jurisdiction

The DHS network preliminary design would have the following routing: *node 1,l* is served by all three supply nodes; node *2,i* supplies both cluster node *1,l* and *1,o* directly; node *2,j* supplies the transshipment node *2,p* which then supplies node *1,l*; and node *2,k* supplies nodes *1,m* and *1,n* directly, while also supplying the transshipment node *2,p* to which then supplies node *1,l*.

Where the pipeline costs were first calculated in section 4.2.5, the pipeline costs are then re-calculated for the determined loads of the DHS network routing.

As previously mentioned, the loss based on cost minimization can be considered for a possible heat upgrade node, or as a potential site for a peak biomass-combusting boiler in the DHS. If added to the system, a new supply node can be added to Table 12 and the dummy node shifts a row down in the table.

4.2.7 Fuel and GHG Savings

Once the preliminary design of the network is determined, GHG savings can be calculated using emissions data for peninsular Halifax, listed in Table 13.

Table 13. GHG emissions for primary heating fuels used in jurisdiction (EnviroCan 2010, NSPI 2006, EPA 2010)

No.	Fuel Type	Greenhouse Gas			
		CO_2	CH_4	N_2O	Units
1	Light fuel oil	2725	0.026	0.006	g/L
2	Electricity	784.7	2.6	1.3	g/kWh

The heat sink cluster types for this jurisdiction use, primarily, either one of two fuel types for space heating and hot water. That is, for the cluster building types identified in Table 11, approximately 43% of buildings use electricity and approximately 37% of buildings use light fuel oil for space heating and domestic hot water combined (NRCan 2008). The fuel and emission savings are shown in Table 14.

Table 14. Fuel savings and GHG emissions for jurisdiction

		Node				
		l	*m*	*n*	*o*	TOTAL
	Existing Energy Demand (MWh)	4185	3456	1647	2167	11456
Light Fuel Oil	Fuel Combustion Effic. (%)	60	60	60	60	
	Fuel savings (L)	545571	450481	214823	282433	1493308
	CO_2 emission savings (tonnes)	1487	1228	585	770	4069
	CH_4 emission savings (grams)	14185	11713	5585	7343	38826
	N_2O emission savings (grams)	3273	2703	1289	1695	8960
Electricity	Fuel savings (MWh)	4185	3456	1648	2167	11456
	CO_2 emission savings (tonnes)	3284	2712	1293	1700	8989
	CH_4 emission savings (tonnes)	11	9	4	6	29
	N_2O emission savings (tonnes)	4	4	2	2	12

Based on kWh energy intensity—an indices function of area described earlier—for the building types, the annual energy demand of the heat sink cluster nodes is calculated to be 4185 MWh for $n_{1,l}$*; 3456 MWh for $n_{1,m}$; 1647 MWh for $n_{1,n}$; and 2167 MWh for $n_{1,o}$. A furnace efficiency of 60 percent (NRCan 2009) is assumed as normal for buildings using light fuel oil (LFO).

As illustrated in Table 14, utilizing the waste heat identified in such a DHS network will reduce CO_2e emissions by 4073 tonnes if all clusters were originally using light fuel oil. If the same clusters were switching from electricity, there will be a reduction of 13227 tonnes of CO_2e.

4.3 DHS Network and Energy Security

The benefits of the preliminary network design on energy security for the jurisdiction can be discussed in terms of its contribution to the four 'R's of energy security described in section 1.1.1. Specifically, the proposed method and subsequent implementation review the energy supplies available through waste heat sources in mixed-use jurisdictions and propose a strategy to replace or restrict the fuel type traditionally used for SH and DHW with one that is more secure.

Nova Scotia's supply of refined petroleum products (and thus LFO use in Halifax), is almost exclusively imported. RPP represent 63%, or 50 TWh, of the province's total energy supply (Hughes 2007). The province consumes approximately 7,700 GWh of LFO per year in the residential, commercial, and institutional sectors (StatsCan 2010). Table 14 shows that utilizing the waste heat sources in the proposed DHS would result in a reduction of about 16 GWh from the overall provincial LFO consumption (if all buildings connected to the DHS were using LFO.)

The total single-detached (i.e. type RES1,2) residential space heating demand (for SH and DHW) in North End Halifax is estimated to be 130GWh; if this demand was met by 60% efficient furnaces, the total LFO demand would be about 215GWh. In clusters

---

* Adjusted for yearly demand considering supply shortfall from DHS.

n1,l and n1,o, buildings restricting their heating supply to the DHS would displace about 8.9 GWh of LFO or 4.1% of the North End's single-detached residential heating demand.

Assessing the total reduction for the jurisdiction requires data on commercial and institutional buildings of the jurisdiction categorized by land parcel, as well as a detailed breakdown of heating system by cluster. The parameters chosen for this case study, described in Table 11, are building type and insulation.

4.4 Summary

The implementation of the method was described, including a discussion on its use of ArcGIS and Excel software to identify heat sources and sink clusters, determine a preliminary design for a DHS primary network, and determine the network's effect on GHG emissions.

Results and discussion have been presented for the method's implementation using a case study of North End Halifax. The sources and sink clusters are identified, and the DHS network routing is determined—using a minimization of cost algorithm—for the mixed-use jurisdiction. Total cost of the primary distribution network, along with the fuel savings, GHG emission reductions, and the impact on energy security associated with the DHS implementation were presented and discussed.

The results showed that connecting part of North End Halifax to the DHS meant that energy security was improved since the demand for electricity or light fuel oil from non-secure sources was reduced and, concomitantly, GHG emissions were reduced.

CHAPTER 5 : CONCLUSIONS

With rising oil prices and energy imports supplied by volatile regions impacting energy security, increasing evidence of climate change, and an economic downturn as pivotal issues of survival in contemporary North America, options for reducing energy consumption—as well as replacing supply and infrastructure—are of critical importance.

While the relationship between cities and their environment—resource extracting and waste dissipating—has been described as parasitic and untenable in the face of the mounting concerns described, cities also hold immense opportunity.

A city's characteristics of mixed-use zoning, diverse built form, high-density development, and residual heat generation by urban processes, present potential for optimizing the thermal energy end-use of certain waste streams.

By applying techniques of systems analysis, energy potential mapping, and linear programming to urban energy planning, various stakeholders of a mixed-use jurisdiction can begin identifying thermal energy potentials. They can then screen and predict a network capitalizing on these potentials, and appropriately matching energy sources and sinks.

The central objective of this research was met. Specifically, a method has been developed to identify sources of waste thermal energy and heat demand clusters in a mixed-use jurisdiction. In identifying this waste heat, a preliminary design for a DHS primary network has been developed with an energy end-use sequence and network routing based on a minimization of cost.

The method is based upon energy potential mapping techniques (GIS spatial analysis) and linear programming algorithms. Another objective accomplished by the research was implementing the method and applying it to a case study of data for peninsular Halifax.

The final objective met by this research was accounting for and discussing the method and implementation's influence on climate change (i.e. a reduction in GHG emissions) and energy security, two central themes of this research.

From this research, the following observations were made with regard to energy planning in mixed-use jurisdictions:

- A review of sources and sinks in a jurisdiction, the first 'R' of energy security, is an imperative step to determining subsequent steps for energy systems development. In this research, the systems analysis discussion represents a broad analytical approach to assess the jurisdiction's energy flows and energy systems. The identification component of the method is a detailed analytical approach to reviewing the energy flows and energy systems.

- In future developments, co-locating certain heat-intensive process industries in cities with mixed-use zoning can generate opportunities for simultaneously recovering losses and mitigating emissions from energy systems. While the environmental and health-related impact of certain industries may already be considered acceptable in their proximity to residential zoning, for example, there is incentive for a more holistic siting of building types or activities.

- Screening tools, such as the method proposed by this research, can accompany already established decision-making methods of community planning for district energy systems. It is meant to coincide with the consultative process of site selection based on end-user interest by buildings or neighborhoods of the specific jurisdiction.

There were also a number of limitations and assumptions associated with the method employed. For instance, the preliminary DHS network design component of the method does not consider the transmission losses or system costs associated with the

DHS heat exchangers. These costs would be incurred at the point-source of the waste heat hubs, in the primary system, as well as at the individual buildings of the sink clusters.

Consequently, a more rigorous analysis would include a cost component, accounting for efficiency and losses, of heat recovery technologies. Further discussion on the technologies and other limitations of the method are discussed in Appendix 1.

Also, the flow variable associated with each of the arcs can be weighted depending on a number of parameters. For example, a district heating system network can have a different sequence routing result depending on whether the flow is measured by temperature, exergetic potential, or energy consumption. These relationships are described in the literature review section, Chapter 2. While the research discusses the use of both energy and exergy in the method, the implementation was based on thermal energy flows and losses.

Finally, it is worth noting that in designing a district cooling system, or combined district heating and cooling system, load profiles for the entire year—not just the heating season—should be considered. A district heating system was selected as the focus of this research to simplify the function, and thus complexity, of the distribution network. Also, as per the case study used in the implementation section, district heating systems are more attractive for jurisdictions with climates having long heating seasons; those regions with a higher value of heating-degree days than cooling-degree days, for example.

The logistical dilemma involved in assuming a holistic approach to energy use planning within a mixed-use built environment can seem daunting. This research contributes, in part, to the body of research focused on a systems-based understanding of energy potentials in cities.

Inasmuch as a specific technical method has been proposed, it is also intended that the overarching framework for addressing the central themes of this research be used as a spring-board for future work.

5.1 Future Work

As discussed in Chapter 2, cities with mixed-use jurisdictions can hold great potential for recovering thermal energy typically lost in industrial processes.

Much progress is to be made in understanding and identifying waste resources as potential sources of energy supply, classifying them in terms of their quantitative and qualitative characteristics, and determining their optimal use.

There are a number of opportunities for future research to be done on the recovery and application of waste heat, in DHS network design, for mixed-use jurisdictions. These include:

- Implementing the method based on exergy flows with the objective function of the design algorithm determining a minimization of both the exergetic efficiency *and* financial cost for the network.

- Assessing feasibility of ground-source heat pumps as a secondary source for a waste heat-based DHS system can make up for shortfalls in unbalanced transshipment problems.

- Acquiring accurate data on temperatures and flow rates of discharge streams among various industrial/commercial processes in mixed-use developments for a more robust linear programming algorithm with a multi-objective function.

- Developing a comprehensive energy-use and process heat database based on industry indices for commercial and industrial operations would benefit the modeling of waste hubs.

- Performing a materials balance of each of the industries in the waste hubs can further identify opportunities to capitalize on bio-energy (see Chapter 2 for further discussion) as additional supply to the DHS.

- Carrying out a detailed cost analysis of secondary network components comprised of heat transfer stations and thermal storage units for the building clusters served; also examining, in detail, the financing of such a DHS, including secondary network capital costs and connection fees.

- Applying the proposed model to a more complex district energy system, including electricity generation and cooling loads.

It is hoped that by furthering the collection of comprehensive data and improvement of supportive tools for this type of research, populations can develop their cities through an energy planning approach that is more holistic, environmentally-sound, and energy-secure.

APPENDIX 1

Assumptions and Limitations

As with any complex system, a number of assumptions and limitations must be imposed on the analytical approach in both its design and implementation to produce results. The following section outlines the constraints on the method, generally, and in the implementation specifically.

i. System Boundaries

The boundaries of the system must be defined by the user before the method can be applied. This task may seem somewhat subjective, however there are a number of practical considerations to limit its perimeters.

Different configurations and boundaries to the system will inevitably lead to different optimization results (Unger, et al. 2010). The system can be defined by the upstream system boundary, technological system boundary, or geographical system boundary; all of which can help represent the life cycle of energy or material flows between the system and its environment.

Upstream system boundaries define individual industries or hubs such as industrial parks within a jurisdiction and are useful when optimizing profitability or feasibility of a DES (Thollander, Svensson and Trygg 2010). Conversely, technological system boundaries can include the industries as well as the utility, comprising the conversion or upgrading technologies of the distribution system.

Geographical system boundaries for a district heating system can be based on such categorizations as land use type, socioeconomic zones, and population densities. All categories vary across the urban landscape, which means the energy planner must decide which parameters are most critical to define the system boundaries for the mixed-use jurisdiction. It should be noted that boundaries move over time depending on trends in development.

In the implementation section, a boundary based on socioeconomic similarities has been selected; such systems, typically referred to as "neighborhoods" in census data, provide easily definable boundaries by their outermost streets.

ii. Assigning Weights

The flow variable associated with each of the arcs can be weighted depending on a number of parameters. For example, network optimization for any district heating system can have a different sequence routing result depending on whether the flow is measured by temperature, exergetic potential, or energy consumption. These relationships are described in the literature review section, Chapter 2.

iii. Time Growth

As with any transmission grid, load availability and demand profiles change over time. Load forecasting commonly predicts growth based on outdoor temperature and energy-use behaviors of the system's users within a year.

For projected growth over longer periods of time, population growth or land use growth by type can be factored into energy intensities or thermal density figures for sources and sinks (Gilmour and Warren, Advancing District Energy Development in Canada: A Process for Site Selection, Review and Community Participation 2007).

Given shifts in zoning regulations, improvements in building energy performance, and variations in process heat production, future methods need to account for sensitivities of the DHS. The method does, however, account for growth using a DHS pipe over-sizing factor that can be adjusted by the user.

iv. Economic Analysis

While calculating the cost associated with the route of the optimized network, the method does not determine the fuel cost (i.e. $/MBTU's) to the individual consumers of the DHS utility. This depends on the costs associated with the secondary system as well, which is subject to a number of other design considerations, as described in the subsequent section.

Furthermore, local subsidies and cost of primary energy must be factored in to establish life-cycle costing of the system. Such economic factors fall outside the scope of this thesis.

v. Primary and Secondary System Exchangers

As discussed in section 5.0, the network optimization does not consider the transmission losses or system costs associated with the DHS heat exchangers.

A more comprehensive analysis would include costing, while accounting for efficiency and losses, of heat recovery technologies. These technologies are able to utilize gas, liquid or steam media on either the recovery side or end-user side over a range of temperatures (Lokuch 1980). Their efficiencies can range from 40 to 80 percent.

Waste heat recovery can be accomplished in one of four different ways; through direct usage, where the discharge heat is used directly in its available form; by the use of heat exchangers, which allows for the heat transfer between two separate streams so no contamination or mixing occurs; with heat pumps, which utilize mechanical work to raise the lower temperature of discharged heat to a higher temperature output; and vapour recompression, which compress a low-temperature waste vapour as a means of driving up the temperature or pressure to increase its usefulness.

It should be noted that, for the latter two methods of heat recovery, energy inputs are required to 'pump' or 'compress' the discharge stream. The fraction of energy input to energy output for the systems are expressed by their *coefficients of performance* (COP), which describes the amount of upgrading (or energy added to the system) required to boost the temperature differential from the heat input to the heat output.

Heat pumps, which operate under the vapour compression cycle, can be used for heat recovery in a number of commercial or small city-sized industrial applications. Food processing plants, for example, typically carry refrigeration systems using ammonia with chiller-produced excess heat expelled into the surrounding environment. Heat recovery heat pumps can compress the refrigerant to upgrade the heat where it is useful in space heating or DHW settings (EPRI 2008). Combining this with an open-loop or ground-source system matches the heat supply with the thermal characteristics of the ground in the urban environment.

These systems typically use plate-and-frame type heat exchangers to avoid contamination of groundwater resources. They are conducive to energy storage in a multi-use urban planning scenario given the stability of ground temperatures throughout the year at depths of 9 metres or more. As decentralized units in a neighborhood, they are flexible and space-saving (NRCan 2002) with ground loops, for example, being vertically-integrated into the urban landscape. This is critical in a building environment that is ever-expanding in a land-constricted city space.

Such a system has the obvious benefits of displacing the carbon emissions otherwise produced by combusting fuel for space heating in the area, as well as recycling the waste heat usually released by the commercial or industrial processes.

As a guiding point for energy planning, Table 3 highlights technical considerations for utilizing heat transfer technologies based on the quality and temperature of the waste stream.

Table 15. Heat Recovery Technologies and Parameters (EMR 1985, Lokuch 1980)

Heat Transfer Technology	**Specifications for Waste Heat Recovery**							
	Low-Temp (<0 – 120°C)	**Med-Temp** (120 – 650°C)	**High-Temp** (>650°C)	**Large Temp Δ?**	**No cross-contamin.**	**Gas-to-gas HX**	**Gas-to-liquid HX**	**Liquid-to-liquid HX**
Shell-and-tube exchanger	■	■		■	■		■	■
Finned-tube HX*	■	■		■	■		■	
Waste heat boiler	■	■			■		■	
Spiral HX	■	■			■			■
Concentric tube HX	■	■		■	■		■	■
Conc. tube HX recuperator		■	■	■	■	■		
Plate HX	■	■		■	■	■	■	■
Run-around system	■	■		■	■	■	■	■
Heat-wheel metallic	■	■			▒ 2	■		
Heat-wheel hydroscopic	■				▒ 2	■		
Heat-wheel ceramic		■	■	■		■		
Heat pipe	■	■		▒ 1	■	■		

1. Limited by the phase equilibrium properties of the internal fluid.
2. With addition of purge section, cross-contamination limited to <1% by mass.
3. * HX : heat exchanger

Economic analyses of the heat recovery technologies are generally subject to economies of scale, technological availability, climatic considerations and adaptability to building function. Using an exergy-based economic analysis we can determine the annual capital and operational costs associated with heat exchanger technology (Shuangying and Yourong 2000), for example, by:

$$C = C_e \tau \left(\Delta E_T + n \Delta E_F \right) + I$$

With the total annual cost, C, equaling the annual capital cost (I) added to the product of the calculated unit price of exergy C_e by τ, being the annual operating time, multiplied by the sum of exergy loss at the absolute temperature (ΔE_T) plus the exergy loss at the operating pressure (ΔE_P) by n, representing the compromised coefficient between exergy and mechanical work. This coefficient is typically in the range of between three and five (Zhenwei 1985).

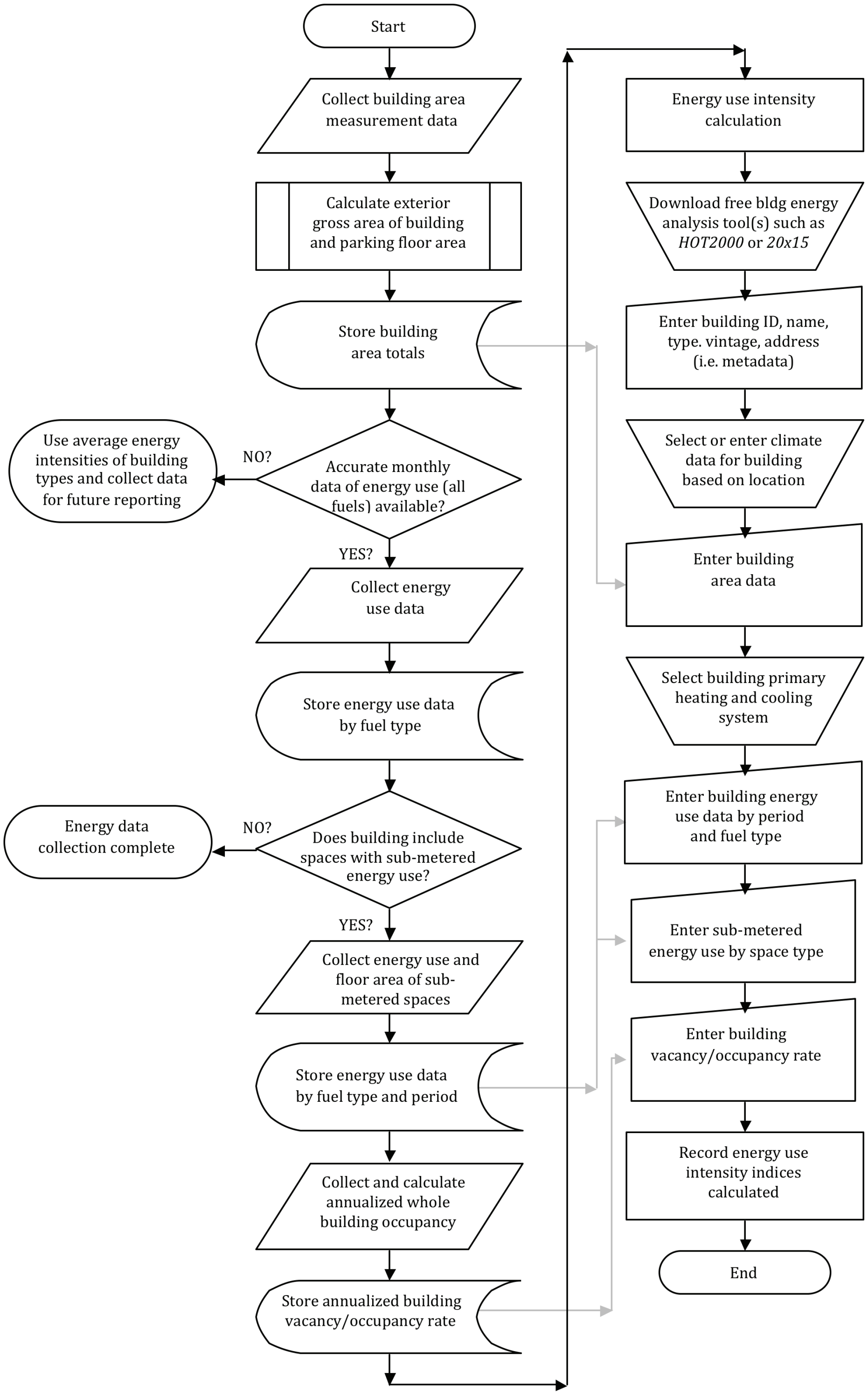
vi. District Cooling and District Energy

In designing a district cooling system, or combined district heating and cooling system, load profiles for the entire year –not just the heating season- must be considered. A district heating system was selected as the focus of this research to simplify the function, and thus complexity, of the distribution network.

Also, as per the case study used in the implementation section, district heating systems are more attractive for jurisdictions with climates having long heating seasons; those regions with a higher value of heating-degree days than cold-degree days, for example.

APPENDIX 2

Figure: Methodology flow chart for calculating building energy intensity (RealPAC 2010)



APPENDIX 3

Pipe Heat Loss Equations

$$Q_{loss} = 2 \times \left[\frac{\left(T_w - T_a\right)}{R_t} \right]$$

where: T_w = Temperature of the pipeline as an arithmetic average of the return T_r and supply lines T_s in K; $T_w = (T_s + T_r)/2$

T_a = Daily average outdoor temperature in K

R_t = Thermal resistance of pipe in mK/W; $R_t = R_i + R_b + R_c + R_s$

R_i = Thermal resistance of insulation material = $\dfrac{\ln\left[\left(r_o + r_{oi}\right) \big/ r_o\right]}{2\pi k_i}$

R_b = Thermal resistance of the channel hole = $1/\left(2\pi r h_b\right)$

R_c = Thermal resistance of the channel = $\dfrac{\ln\left[\left(r_c + t_c\right)/r_c\right]}{2\pi k_c}$

R_s = Thermal res. of the soil = $\left(\dfrac{1}{2\pi k_s}\right) \ln\left[h_c \big/ r_c \left\{ 1 + \sqrt{1 - \left(D_T \big/ h_c \right)^2} \right\} \right]$

h_b = Burial depth to the centerline of the channel hole in m;

$$h_b = \left(k_i / D_T\right) \times \left[0.60 + \frac{0.387 Ra_D^{1/6}}{\left(\left(1 + (0.559/\mathrm{Pr})^{9/16}\right)^{8/27}\right.} \right]^2$$

h_c = Burial depth to the centerline of the pipe in m

k_i = Thermal conductivity of the insulation material in W/mK

k_c = Thermal conductivity of the channel material in W/mK

k_s = Thermal conductivity of the soil in W/mK

D_T = Diameter of the insulated pipe in m

r_c = Radius of the channel in m; $r_c = CC/2\pi$

r_o = Outer radius of pipe in m

r_{oi} = Thickness of insulation in m

t_c = Thickness of the channel in m

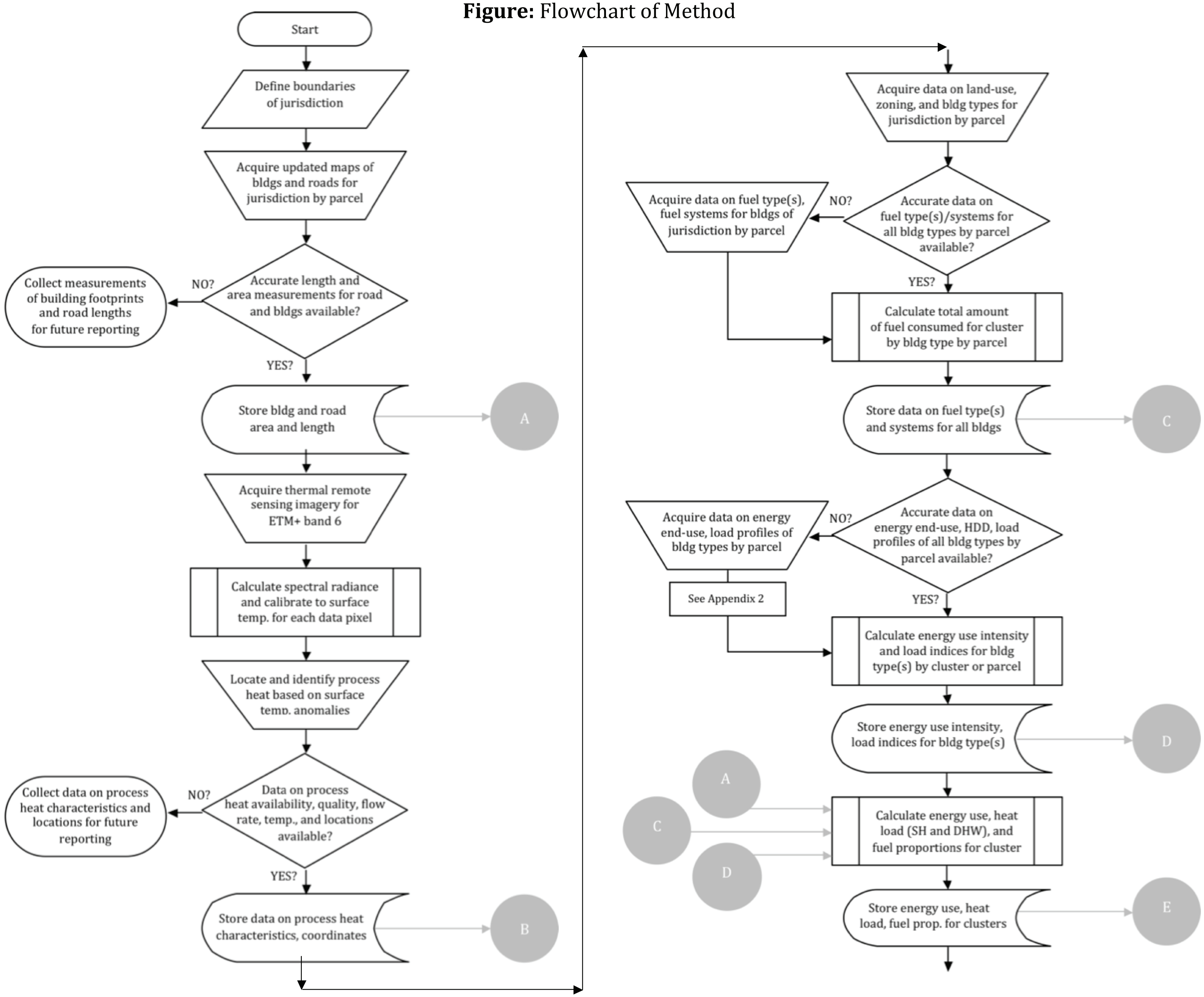
CC = Circumference of the channel in m

Ra = Rayleigh number

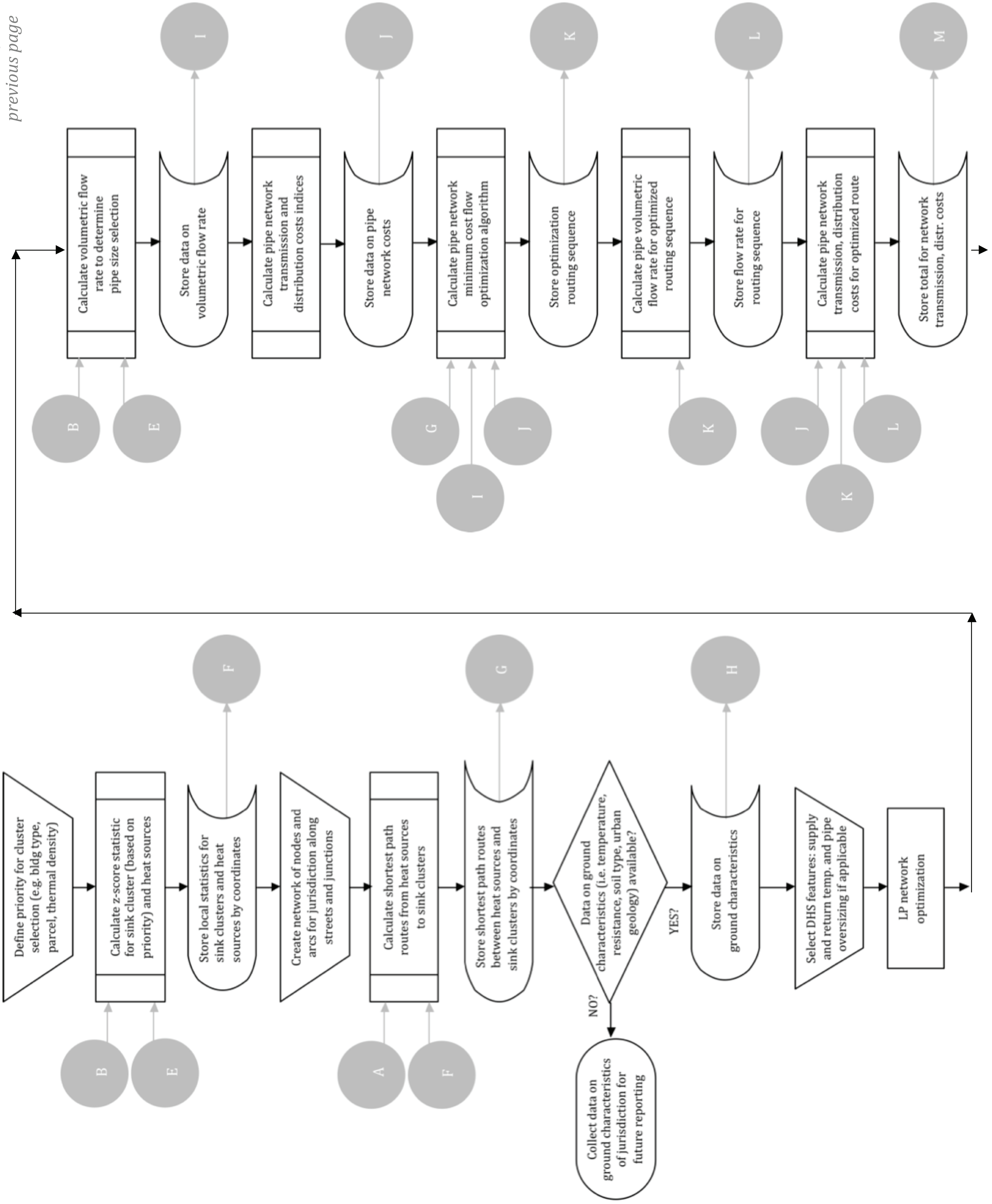
Pr = prandtl number

APPENDIX 4

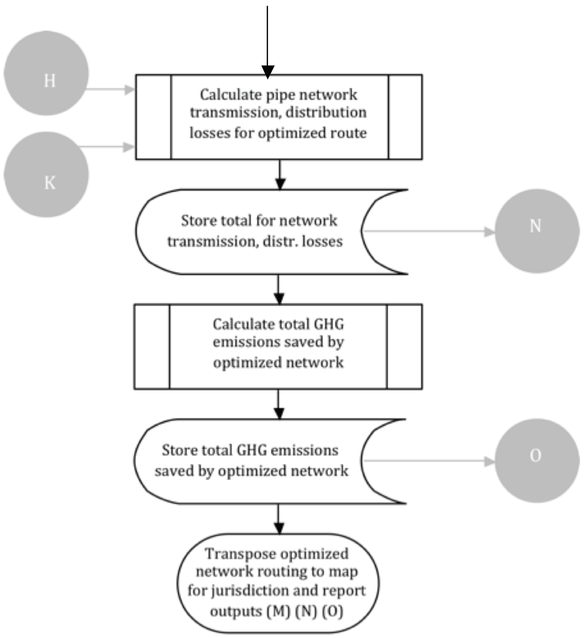
Figure: Flowchart of Method



Continued from previous page



Continued from previous page



BIBLIOGRAPHY

Ajah, Augustine N., Anish C. Patil, and Paulien M., Grievink, Johan Herder. “Integrated conceptual design of a robust and reliable waste-heat district heating system.” *Applied Thermal Engineering* 27 (2006): 1158-1164.

Antonoff, Jayson. “Scandinavia taps power of district energy systems.” *i-Sustain.* Seattle, 2004 йил 26-May.

APA. *Planning and urban design standards.* Edited by American Planning Association. Hoboken, NJ: John Wiley & Sons, 2006.

APERC. *A Quest for Energy Security in the 21st Century.* Institute of Energy Economics, Tokyo: Asia Pacific Energy Research Centre, 2007.

Arkay, Katherine E., and Caroline Blais. *The district energy option in Canada.* Ottawa: Natural Resources Canada, 1996.

ASHRAE. *ASHRAE Handbook of HVAC Systems and Equipment.* Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc, 2000.

—. *Fundamentals.* New York: American Society of Heating, Refrigerating and Air Conditioning Engineers, 2005.

—. *Handbook of Fundamentals.* New York: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc., 1972.

ASHRAE. “Thermodynamics and Refrigeration Cycles.” In *Fundamentals*, by ASHRAE, 1-15. New York: ASHRAE, 2005.

BAAQMD. *Coffee Roasting Handbook.* 2009 йил 5-March. http://www.baaqmd.gov/ (accessed 2009 йил 2-April).

Balmér, P. “Energy conscious waste water treatment plant.” *CADDET Energy Efficiency Newsletter*, 1997 йил June: 11-12.

Bamforth, C.W. *Brewing: New Technologies.* New York: Woodhead Publishing Limited, 2006.

Bell, Mike. *Development of Micro-CHP Technology Assessment Capability at CCHT.* June 2005 Technical Series 05-102, Ottawa: Canadian Centre for Housing Technology (CCHT), 2005.

Bertsekas, Dimitri P. *Network Optimization: Continuous and Discrete Models.* Belmont: Athena Scientific, 1998.

Bose, Ranjan K. *Energy efficient cities: assessment tools and benchmarking practices.* Washington, D.C.: World Bank, 2010.

Briggs, Dennis E, et al. *Brewing: Science and Practice.* New York: Woodhead Publishing Limited, 2004.

Broersma, Siebe, and Andy van den Dobbelsteen. *Energy transition in South Limburg.* Report, Faculty of Architecture, Delft University of Technology, SREX, 2008.

Brown, Marilyn A. and Southworth, Frank, and Andrea Sarzynski. *Shrinking the carbon footprint of metropolitan America.* Report, Metropolitan Policy Program, Washington: Brookings Institution, 2008.

Bruno, S., S. Lamonaca, M. La Scala, and U. Stecchi. *Optimal Design of Trigeneration and District Energy in the Presence of Energy Storage.* Research Report, Bari: European Association for the Development of Renewable Energies, Environment and Power Quality, 2010.

Butler, J. Allison. *Designing Geodatabases for Transportation.* Redlands: ESRI Press, 2008.

CANMET. *Community Energy Technologies.* Energy Technology Centre-Ottawa, Ottawa: Natural Resources Canada, 1997.

Caputo, A. C., G. Cardarelli, and P. M. Pelagagge. "Analysis of heat recovery in gas-solid moving beds using a simulation approach." *Applied Thermal Engineering* 16 (1996): 89-99.

CCME. *Climate, nature, people: indicators of climate change.* Report, Winnipeg: Canadian Council of Ministers of the Environment, 2003.

CCOG. *GeoBase.* Canadian Council on Geomatics. 2010 йил 29-June. htpp://www.geobase.ca (accessed 2010 йил 8-July).

CDEA. *The New District Energy: Building Blocks for Sustainable Community Development.* On-Line Handbook, Canadian District Energy Association, Toronto: Infrastructure Canada, 2008.

CEC. *An Energy Policy for Europe.* Communication from the Commission to the European Council and the European Parliament, 2007: Commission of the European Communities, 2007.

CEM. *Moving forward on energy efficiency in Canada.* Ottawa: Council of Energy Ministers, 2007.

Cengel, Yunus A., and Michael A. Boles. *Thermodynamics: an engineering approach.* 6th Edition. Boston: McGraw Hill, 2008.

Chang, Y.J., and C.C. Wang. "A generalized heat transfer correlation for louver fin geometry." *International Journal of Heat and Mass Transfer* 40 (1997): 533-544.

Charyulu, D.G., G. Singh, and J.K. Sharma. "Performance evaluation of a radiator in a diesel engine - a case study." *Applied Thermal Engineering* 19 (1999): 625-639.

Ciavaglia, L. *Personal communication, CANMET Energy Technology Centre-Ottawa, Natural Resources Canada.* (2003).

CMHC. *Insulation Effectiveness.* 2010 йил 21-March. http://www.cmhc-schl.gc.ca/ (accessed 2011 йил 11-January).

Coles, Associate Ltd. *Heat demand surveys Charlottetown and Summerside cogeneration projects.* Report, PEI Energy Corporation, Charlottetown: PEI Department of Energy and Forestry, 1990.

Collins. *Collins English Dictionary – Complete and Unabridged .* New York: HarperCollins Publishers, 2003.

Comakli, Kemal, Bedri Yuksel, and Omer Comakli. “Evaluation of energy and exergy losses in district heating network.” *Applied Thermal Engineering*, no. 24 (2003): 1009-1017.

Concerto. *Polycity - City of Stuttgart (Ostfildern).* 2009 йил 24-March. http://www.concertoplus.eu/cms (accessed 2010 йил 5-October).

Crane, Douglas T., and Gregory S. Jackson. “Systems-level optimization of low-temperature thermoelectric waste heat recovery.” *37th lntersociety Energy Conversion Engineering Conference (IECEC).* Maryland: IEEE, 2002. 583-591.

Crawley, Drury B., Linda K. Lawrie, Curtis O. Pedersen, and Frederick C. Winkelmann. “EnergyPlus: A New-Generation Building Energy Simulation Program.” *Renewable and Advanced Energy Systems for the 21st Century.* Maui: U.S. Department of Energy, 1999.

CURE. *Building knowledge for a changing climate.* Brochure, Centre for Urban and Regional Ecology, School of Planning & Landscape, University of Manchester, Manchester: UK Climate Impacts Programme, 2003.

De Monte, Michele, and Elio and Pozzetto, Dario Padoano. “Waste heat recovery in a coffee roasting plant.” *Applied Thermal Engineering*, no. 23 (2003): 1033–1044.

Diamant, R.M.E., and David Kut. *District heating and cooling for energy conservation.* London: The Architectural Press, 1981.

Dinçer, İbrahim, and Marc A. Rosen. *Thermal energy storage.* Chichester: Wiley, 2002.

Dincer, Ibrahim, and Marc A. Rosen. *Exergy: energy, environment and sustainable development.* Oxford: Elsevier, 2007.

DMTI. *DMTI Spatial Inc. Data.* Prod. Desktop Mapping Technologies Inc. Markham, 2010 йил 1-August.

Dobbelsteen, Andy V. D., Machiel V. Dorst, and Arjan V. Timmeren. *Smart building in a changing climate.* Amsterdam: Techne Press, 2009.

Dobbelsteen, Andy van den, Sabine Jansen, Anne-Lorène Vernay, and Leo and Gommans. “Building within an energetic context - Low-exergy design based on local energy potentials and excess or shortage of energy." Singapore: 24th Conference on Passive and Low Energy Architecture, 2007. 1-6.

Dodd, Nick. *Community energy: urban planning for a low carbon future.* Report, Hollinwood: TCPA & CHPA (Town and Country Planning Association and the Combined Heat and Power Association), 2008.

Dorer, Viktor. *Residential Cogeneration Systems: A Review of The Current Technologies.* Subtask C of FC+COGEN-SIM, Ottawa: International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2007.

Doukas, Alex. *Distributed Generation in Canada - Maximizing the benefits of renewable resources.* Background Report, Toronto: Canadian Renewable Energy Alliance, 2006.

EIA. *Environmental Data.* 2010 йил 12-August. http://www.eia.gov/environment/data.cfm (accessed 2010 йил 30-August).

Emmanuel, M. Rohinton. *An urban approach to climate-sensitive design.* New York: Spon Press, 2005.

EMR. *Waste heat recovery.* Energy Management Series, Ottawa: Energy, Mines and Resources Canada, 1985.

Entchev, E. and Gusdorf, J., M. Swinton, M. Bell, F. Szadkhowski, W. Kalbfleisch, and R. Marchand. *Micro-generation technology assessment at the Canadian Centre for Housing Technology.* Assessment, Ottawa: Canadian Centre for Housing Technology, 2004.

EnviroCan. *Canada's Greenhouse Gas Inventory 1990–2003.* 2003 йил 2-May. http://www.ec.gc.ca/pdb/ghg/inventory_e (accessed 2010 йил 19-April).

—. *Fuel Combustion.* 2010 йил 12-08. http://www.ec.gc.ca/ges-ghg (accessed 2010 йил 06-10).

EPA. *eGRID: Coal.* 2010 йил 1-March. www.epa.gov/cleanenergy/energy-and-you/affect/coal.html (accessed 2010 йил 4-September).

EPRI. *Use of Heat Recovery Heat Pumps for Heating Water in Industrial Plants.* Information sheet, Palo Alto: Electric Power Research Institute, 2008.

Erhorn, Heike Kluttig. *Stuttgart–Burgholzhof.* 2010 йил 13-July. http://www.buildup.eu/cases/10211 (accessed 2010 йил 21-August).

ESRI. *How Hot Spot Analysis (Getis-Ord Gi*) works .* 2010 йил 1-January. http://help.arcgis.com/en/arcgisdesktop (accessed 2010 йил 17-August).

Fadare, D.A., D.O. Nkpubre, A.O. Oni, A. Falana, M.A. Waheed, and O.A. Bamiro. "Energy and exergy analyses of malt drink production in Nigeria." *Energy* (Elsevier), no. 35 (2010): 5336-5346.

Farahbakhsh, Hamid, Alan S. Fung, and V. Ismet Ugursal. *Archetypes: Space heating thermal requirements and unit energy consumption of Canadian homes in 1993.* Final

Report, Canadian Residential Energy End-use Data and Analysis Centre, Ottawa: NRCan, 1997.

Fehrm, Mats, and Wilhelm and Ungemach, Matthias Reiners. “Exhaust air heat recovery in buildings.” *International Journal of Refrigeration*, no. 25 (2002): 439–449.

Feustel, H.E., and Th.P. Lenz. “Patterns of infiltration in multi-family buildings.” *Building and Environment* 20, no. 1 (1985): 7-13.

Fisk, David. *Urban Energy Systems.* Colloquium, London: Factor 10 Engineering for Sustainable Cities, 2006.

FPD. “Oland Breweries investing in Nova Scotia brewery.” *Food Production Daily*, 2002 йил 10-May.

Frece, John W. “Smart growth and neighbourhood conservation.” Plan Canada, 2001.

GA. *Bound for Success: A Citizen's Guide to Using Urban Growth Boundaries for More Livable Communities and Open Space Protection in California.* Report, San Francisco: Greenbelt Alliance, 1997.

Galitsky, Christina. “Energy Efficiency Opportunities and Potential Cost Savings for United States Breweries.” *Technical Quarterly* (MBAA) 38, no. 4 (2001): 189-198.

Gilmour, Brent. *Canadian census of district energy owners and operators.* Census, Urban Energy Solutions, Canadian Urban Institute and the Canadian District Energy Association, Toronto: Infrastructure Canada, 2007.

Gilmour, Brent, and John Warren. *Advancing District Energy Development in Canada: A Process for Site Selection, Review and Community Participation.* Report, Canadian District Energy Association, Toronto: Urban Energy Solutions Initiative, 2007.

Gilmour, Brent, and John Warren. *Advancing District Energy Development in Canada: A Process for Site Selection, Review and Community Participation.* Report, Toronto: Canadian District Energy Association, 2007.

Gilmour, Brent, and John Warren. *District Energy: A National Survey Report.* Report, Toronto: Canadian District Energy Association, 2009.

Gilmour, Brent, and John Warren. *The New District Energy: Building Blocks for Sustainable Community Development.* On-line Handbook, Canadian District Energy Association, Ottawa: Infrastructure Canada, 2008.

GISC. *Spatial datasets for Nova Scotia and Halifax Regional Municipality.* Prod. Geographical Information Systems (GIS) Centre. Halifax, NS, 2010 йил 4-October.

Goupil, Jennifer. “History repeats itself: Mixed-use developments can leverage shared resources and also inspire a sense of community.” *Structural Engineering and Design*, 2008.

Grammenos, Fanis. *Smart Growth in Canada: A Report Card.* Socio-economic Series 05-036, Ottawa: Canada Mortgage and Housing Corporation, 2005.

Grant, Jill. “Encouraging mixed use in practice.” *International Planning Symposium on Incentives, Regulations, and Plans – The Role of States and Nation-States in Smart Growth Planning.* Netherlands: National Center for Smart Growth Research and Education, 2004. 1-21.

Gregory, Ed. *Personal communication with Manager of Research and Analysis, Brewers Association of Canada* (2011 йил 16-January).

Guyer, Howard H. *Industrial process and waste stream management.* New York: Wiley, 1998.

Haidar, Jihad G., and Jamil I. Ghojel. “Optimization of the Thermal Regime of Thermoelectric Generators in Waste Heat Recovery Applications.” *21st International Conference on Thermoelectronics.* IEEE, 2002. 427-430.

Harvey, Danny L.D. *Low-energy buildings and district energy systems: fundamentals, techniques and examples.* London: Earthscan, 2006.

Hester, Randolph T. *Design for Ecological Democracy.* Cambridge, MA: Massachusetts Institute of Technology, 2006.

Hillier, Frederick, and Gerald Lieberman. *Introduction to operations research.* New York: McGraw-Hill, 2010.

HRM. *By-Law W-101: Respecting discharge into public sewer.* Legislation, Halifax: Halifax Regional Municipality, 2003.

HRM. *HRM Annual Report 06-07.* Annual Report, Halifax: Halifax Regional Municipality, 2007.

—. “Polling District 11: Halifax North End.” *Halifax Regional Municipality.* 2010 йил 1-January. www.halifax.ca/municipalclerk/documents/District11.pdf (accessed 2010 йил 10-November).

HRM. *Regional Planning: Goals and Objectives.* Report, Halifax: Halifax Regional Municipality, 2004.

Hughes, L. “The four A's of energy security and their application.” In *Routledge*, by Sodomos. Halifax: Routeldge Press.

Hughes, L., and D. Ron. *Energy security in the residential sector: rapid responses to heating emergencies.* Report, Halifax: Canadian Centre for Policy Alternatives, 2009.

Hughes, Larry. “Eastern Canadian crude oil supply and its implications for regional energy security.” *Energy Policy*, 2010.

Hughes, Larry. *Energy Security in Nova Scotia.* Report, Ottawa: Canadian Centre for Policy Alternatives, 2007.

Hughes, Larry. *Personal communication with Dr. Larry Hughes, Dalhousie University* Halifax, (2011 йил 15-March).

Hughes, Larry. *The four 'R's of energy security.* Report, Dalhousie University, Halifax: Energy Research Group, 2009.

Hughes, Larry, and Darren Shupe. *The four 'A's of energy security and their application in an energy security ranking method* (Routledge), 2010.

IEA. *Energy Security.* 2010 йил 1-November. http://www.iea.org (accessed 2011 йил 9-January).

IEA. *How the energy sector can deliver on a climate agreement in Copenhagen.* Special early excerpt of the World Energy Outlook 2009 for the Bangkok UNFCCC meeting, Paris: International Energy Agency, 2009.

IEA. *Toward a sustainable energy future.* Report, Paris: International Energy Agency, 2001.

IPCC. *Climate change and biodiversity.* IPCC Technical Paper V, Melbourne: UNEP and WMO, 2002.

J. Mikael Eklund, Ian Spencer, Jinfu Zheng, Neil Yhap, Ryan Naughton, David Mercy, Charles Elliot,.

Jordanger, Einar, Bjørn H. Bakken, Arne T. Holen, Arild Helseth, and Audun Botterud. "Energy distribution system planning- methodologies and tools for multi-criteria decision analysis." *18th International Conference on Electricity Distribution.* Turin: CIRED, 2005.

Kaya, Yoichi and Yokobori, Keiichi. *Environment, energy, and economy: strategies for sustainability.* Tokyo: United Nations University Press, 1997.

Knight, Ian and Ugursal, Ismet. *Residential Cogeneration Systems: A Review of The Current Technologies.* Subtask A of FC+COGEN-SIM, Ottawa: International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2005.

Kruyt, Bert, D P van Vuuren, H J M de Vries, and H Groenenberg. "Indicators for energy security." *Energy Policy*, 2009 йил June: 2166–2181.

Landsat-7. *Orthorectified Imagery over Canada.* Prod. United States Geological Survey. Ottawa: GeoBase, NRCan, 2003.

Latosov, E., and A. Siirde. "Heat load model for small-scale CHP planning." *International Conference on Renewable Energies and Power Quality.* Granada: International Conference on Renewable Energies and Power Quality, 2010.

Le, Minh N. *Modeling and analysis of cogeneration based district energy system.* Thesis, Mechanical Engineering, University of Western Ontario, London: National Library of Canada, 1996.

Leduc, W.R.W.A., and R. Rovers. “Urban Tissue: the representation of the Urban Energy Potential.” *25th Conference on Passive and Low Energy Architecture.* Dublin: PLEA, 2008.

Levent, Tüzin Baycan. *Urban Planning.* Northampton, MA: Edward Elgar Publishers, 2008.

Ligeti, Eva and Penney, Jennifer, and Irene Wieditz. *Cities preparing for climate change.* Report, Toronto: Clean Air Partnership, 2007.

Lokuch, Michael. *Industrial application and assessment of waste heat recovery technologies.* Thesis, Drexel University, Ann Arbor: University Microfilms International, 1980.

Lowerison. “Personal communication with Ron Lowerison, Civic Address Data Control Coordinator for Halifax Regional Municipality.” Halifax, 2011 йил 9-February.

Lukitobudi, A. R., A. Akbarzadeh, and P.W. and Hendy, P.H. Johnson. “Design, construction and testing of a thermosyphon heat exchanger for medium temperature heat recovery in bakeries.” *Heat Recovery Systems & CHP* 15, no. 5 (1995): 481-491.

Major, G. *Small Scale Cogeneration.* Analysis Series 1, Netherlands: CADDET (Centre for the Analysis and Dissemination of Demonstrated Energy Technologies), 1995.

Marnoch, Ian, et al. “Data collection, simulation and design of a waste heat energy conversion system.” *Electrical Power and Energy Conference.* Montreal: IEEE, 2009.

McBean, G, and D. Henstra. *Climate change, natural hazards and cities.* ICLR Research Paper Series, No. 31, Toronto: Institute for Catastrophic Loss Reduction, 2003.

Morofsky, Edward L., and Vikash Verma. *District energy systems analysis.* Ottawa: Public Works Canada, 1979.

NASA. *Landsat 7 Science Data Users Handbook.* Washington: National Aeronautics and Space Administration, 2009 йил 21-October.

NRCan. *Annual Heating Costs of Heating Systems and Energy Savings.* 2009 йил 20-April. http://oee.nrcan.gc.ca/residential/ (accessed 2010 йил 3-September).

NRCan. *Commercial Earth Energy Systems: A Buyer’s Guide.* Informational Publication, Ottawa: Natural Resources Canada, 2002.

NRCan. *Community energy planning guide.* Guide, CANMET Energy Technology Centre, Ottawa: Natural Resources Canada, 2007.

—. *Comprehensive Energy Use Database, 1990 to 2008.* Natural Resources Canada. 2008. http://oee.nrcan.gc.ca/ (accessed 2010 йил 21-05).

—. *Heating Biomass system - District energy / Canada .* Natural Resources Canada. 2009 йил 24-February. http://www.retscreen.net/ang/case_studies_district_energy_canada.php (accessed 2010 йил 13-January).

—. *RETScreen.* 2010 йил 12-May. http://www.retscreen.net (accessed 2010 йил 23-June).

—. *Software Tools: HOT3000.* 2009 йил 24-March. http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/software_tools/hot3000.html (accessed 2010 йил 8-September).

NRCan. *Survey of Household Energy Use (2007).* Detailed Statistical Report, Office of Energy Efficiency, Ottawa: Natural Resources Canada, 2010.

NRCan. *The Urban Archetypes Project - Community Case Study: Halifax Regional Municipality.* Report, CanmetENERGY, Ottawa: Natural Resources Canada, 2009.

NSPI. *CO2 Emission Intensity.* 2006 йил 01-01. http://www.nspower.ca/en/home/environment/emissions/archivedemissionslevels (accessed 2010 йил 15-09).

Ockert, Karl. *Brewing Engineering and Plant Operations.* MBAA Practical Handbook for the Specialty Brewer. Vol. 3. St. Paul: Bridgeport Brewing Company, 2006.

Oke, T.R. “The urban energy balance.” *Progress in Physical Geography* (Sage Publications), no. 12 (1988): 471-508.

OME. *District heating study.* Report, Acres Shawinigan Ltd, Toronto: Ontario Ministry of Energy, 1976.

Orlando, Joseph A. *Cogeneration Planner's Handbook.* Tulsa: PennWell Publishing Company, 1997.

Owen, David. *Green Metropolis: Why Living Smaller, Living Closer, and Driving Less are the Keys to Sustainability.* New York: Riverhead Books, 2009.

Ozgenera, Leyla, Arif Hepbasli, and Ibrahim Dincer. “Energy and exergy analysis of geothermal district heating systems: an application.” *Building and Environment*, no. 40 (2005): 1309–1322.

Patterson, Mike C., and Bob Harmel. “Using Microsoft Excel for Linear Programming Problems.” *International Journal of Management* 18, no. 3 (September 2001): 308-313.

Peckler, D. “The tankless alternative.” *Home Energy* Nov/Dec 2003 (2003): 10.

Pol, Olivier and Costa, Simona. *Planning and implementation of sustainable energy projects in urban areas.* Presentation, Geneva: CONCERTO Plus, 2009.

Polycity. *Cerdanyola-Barcelona.* 2007 йил 1-October. http://www.polycity.net/en/cerdanyola-barcelona-project.html (accessed 2010 йил 8-July).

Prokoph, Andreas. *Urban heat island effect on temperature trends in Eastern Ontario, Canada.* Summary presentation, Carleton University, Ottawa: Speedstat Consulting, 2008.

RealPAC. *20 by '15 – Technical Methodology for Calculating Building Energy Use Intensity.* Circulation Draft, Toronto: Real Property Association of Canada, 2010.

Rees. "An ecological economics perspective." In *Understanding Urban Ecosystems*, by Alan Berkowitz et al. New York: Springer-Verlag, 2003.

Rees, William, and Mathis Wackernagel. "Urban Ecological Footprints: Why Cities Cannot be Sustainable—and Why They are a Key to Sustainability." *Environmental Impact Assessment Review* 16 (1996): 223-248.

Reisman, Ann W. *A handbook of district heating and cooling models.* Washington: International District Heating and Cooling Association, 1986.

Rodrigue, Jean-Paul, Claude Comtois, and Brian Slack. *The Geography of Transport Systems.* London: Routledge Press, 2009.

Rohsenhow, W. M., J. P. Hartnett, and E. N. Ganić. *Handbook of Heat Transfer Fundamentals.* 2nd Edition. New York: McGraw-Hill Book Company, 1985.

Rovers, R, Claudia Agudelo, and Adriaan Mels. "Urban water tissue: analysing the urban water harvest potential." In *Smart building in a changing climate*, by Andy V. D. Dobbelsteen, Michael V. Dorst and Arjan V. Timmeren, 63-78. Amsterdam: Techne Press, 2009.

Rovers, R. "Urban harvest and the hidden building resources." *CIB World Congress.* Cape Town, 2007.

Rubinstein, Alexis. "Green machines are hot for coffee roasters." *Tea & Coffee Trade Journal*, 2007.

Ruest, Ken. *Low Temperature Heating.* Technical Series 00-143, Ottawa: Canada Mortgage and Housing Corporation (CMHC), 2000.

Saaty, T. *The Analytic Hierarchy Process.* New York: McGraw-Hill, 1980.

Sass, Ronald L. *It's not cool to be hot in Houston.* Dept. of Ecology & Evolutionary Biology, Rice University. 2009 йил 12-December. http://www.ruf.rice.edu/~sass/UHI.html (accessed 2010 йил 5-March).

Scheweig, Greg. *Feasibility of wood-fuelled district heating in a remote community.* Thesis, Department of Forestry, University of Toronto, Toronto: UofT, 1997.

Schneider, E., and J. Kay. "Life as a manifestation of the second law of thermodynamics." *Advances in Mathematics and Computers in Medicine* (University of Waterloo Faculty of Environmental Studies, Working Paper Series), 1992.

Schulze, Matthias. *Network Flow Model for Multi-Energy Systems.* Prod. Swiss Federal Institute of Technology Zurich. Zurich, 2010 йил 25-February.

Shuangying, Wu, and Li Yourong. "Exergy-Economic Criteria for Evaluating Heat Exchanger Performance." *Journal of Thermal Science* 10, no. 3 (2000): 218-222.

Sibbald, John. *Conversation with Environmental Services representative of Halifax Water at Halifax Regional Municipality* (2011 йил 12-February).

Skagestad, Bard, and Peter Mildenstein. *District Heating and Cooling Connection Handbook.* Report, Programme of research, development and demonstration on district heating and cooling, PAris: International Energy Agency, 1999.

Skagestad, Bard, and Peter Mildenstein. *District Heating and Cooling Connection Handbook.* Report, Programme of research, development and demonstration on district heating and cooling, Paris: International Energy Agency, 1999.

Smit, B., I. Burton, R. Klein, and J. Wandel. "An anatomy of adaptation to climate change and variability." *Climatic Change* 45, no. 1 (2000): 233-251.

Smith, Peter F. *Building for a changing climate: the challenge for construction planning and energy.* London: Earthscan, 2010.

Snoek, Chris, Libing Yang, Tom Onno, Svend Frederiksen, and Hans Korsman. *Optimization of district heating systems by maximizing building heating system temperature difference.* Report, Programme of Research, Development and Demonstration on District Heating and Cooling, Paris: International Energy Agency, 2000.

SNS. *Nova Scotia Topographic Databases.* Prod. Nova Scotia Geomatics Centre. Halifax, 2009 йил 15-April.

Spoelstra, S., W.G. Haije, and J.W. Dijkstra. "Techno-economic feasibility of high-temperature chemical heat pumps for upgrading industrial waste heat." *Applied Thermal Engineering* 22, no. 14 (2002): 1619–1630.

StatsCan. *Census Metropolitan Area (CMA) Tracts.* Map, Geography Division, Ottawa: Statistics Canada, 2002.

StatsCan. *Census snapshot of Canada - Urbanization.* Report, Ottawa: Statistics Canada, 2008, 11-12.

StatsCan. *Census Tracts for Halifax CMA.* Census Data, Ottawa: Statistics Canada, 2006.

StatsCan. "Supply and demand of primary and secondary energy in natural units for Nova Scotia, annual (Table 128-0010)." *CANSIM (database),.* Ottawa, 2010 йил 17-February.

Steemers, K. "Energy and the city: density, buildings and transport." *Energy and Buildings*, no. 35 (2003): 3-14.

Stillwell, John, and Graham Clarke. *Applied GIS and spatial analysis.* Chichester: John Wiley & Sons, 2004.

Sullivan, G. P., G. B. Parker, R. Pugh, and Battelle. *Cal-UCONS Commercial Laundry Program Measurement and Evaluation .* Final Report, Pacific Northwest Division, Pacific Gas and Electric, 2008.

Sweatman, A. *LCA of a washing machine.* Report, Bolton: University of Bolton, 2007.

Thollander, Patrik, Inger-Lise Svensson, and Louise Trygg. "Analyzing variables for district heating collaborations between energy utilities and industries." *ENERGY* (Elsevier) 35, no. 9 (2010): 3649-3656.

Towler, Gavin, and Ray Sinnott. *Chemical engineering design: Principles, practice and economic of plant and process design.* Burlington: Elsevier, 2008.

Tucker, G., S. Tena, and J. Quarini. *Utilisation of waste heat from food factories.* Summary, Bristol University, Bristol: CCFRA, 2007.

UDE. *Building Energy Software Tools Directory: ENERPASS.* 2010 йил 14-June. http://apps1.eere.energy.gov/buildings/tools_directory/ (accessed 2010 йил 20-August).

UN. *United Nations Framework on Climate Change.* Article 1, New york: UNFCCC, 1992.

Unger, Thomas, et al. *Coordinated use of energy system models in energy and climate policy analysis.* Report, Stockholm: Nordic Energy Perspectives, 2010.

UN-Habitat. *Cities & climate change: an introduction.* Brief, Nairobi: United Nations Human Settlements Programme, 2009.

Ward, Sarah, and Leila Mohammed. *Sustainable urban energy planning.* Handbook, Geneva: ICLEI Local Governments for Sustainability, UNEP, 2009.

Weizsäcker, Ernst Von, Amory B. Lovins, and L Hunter Lovins. *Factor Four: doubling wealth - halving resource use.* London: Earthscan Publications Ltd, 1997.

Whiston, Darren, interview by Dave Ronn. *Just Us Production Facility* (2009 йил April).

Winston, Wayne L., and Munirpallam Venkataramanan. *Introduction to Mathematical Programming: Applications and Algorithms.* 4th Ed. Pacific Grove: Duxbury Press, 2003.

Yannas, Simos. "Toward more sustainable cities." *Solar Energy* 70, no. 3 (2001): 281–294.

Yap, Lorene Y. L. "The attraction of cities : A review of the migration literature." *Journal of Development Economics* (Elsevier) 4, no. 3 (2002): 239-264.

Yoshikawa, S. "Japanese DHC system uses untreated sewage as a heat source." *CADDET Energy Efficiency Newsletter*, 1997 йил June: 8-10.

Zhenwei, Ni. "Second-Law-Based Thermodynamic Analysis and Evaluating Method." *Journal of Engineering Thermophysics* 6, no. 4 (1985): 311-314.

Zinko, Heimo. *District heating distribution in areas with low heat demand density.* Report, Programme on District Heating and Cooling, including the integration of CHP, Nordborg: International Energy Agency, 2008.