Exploring the Feasibility of Achieving Energy Self-sufficiency — A Residential Electricity Case Study in Ontario

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

As energy security and climate issues are emerging as global concerns, it is commonly agreed that a transition from a conventional centralized energy system, which is largely based on combustion of fossil fuel, to a more sustainable decentralized energy system that includes mainly renewable energy sources is necessary and urgent. Due to the highly variable geographical qualities of renewable energy sources, spatial energy planning is becoming essential. This study aims to address the challenges in linking spatial modeling with assessment of regional energy consumption and renewable energy supply potential.

A novel approach for exploring the feasibility of achieving energy self-sufficiency through matching energy deficit areas with energy surplus areas is proposed. A method for energy deficit and surplus area matching is developed and implemented in a VBA-based tool that serves as a decision-support tool by exploring possible future deployment of renewable energy in decentralized ways.

Achieving Ontario residential electricity self-sufficiency through solar PV energy on an annual basis is explored as a case study. The results show that it is technically feasible for Ontario to be residential electricity self-sufficient through the development of solar PV energy with energy deficit areas within the region getting energy supply from nearby energy surplus areas. The case study implies that regional residential electricity self-sufficiency is achievable and it is useful for planners and policy makers to bear the regional energy deficit-surplus matching idea in mind when making urban and energy plans.

Acknowledgements

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Chapter 1 Introduction

1.1 Research Background

Energy is an essential part of human society and development. From the first fire that was made to the big breakthroughs in industrial and technological revolutions, energy has always played a key role in human history. In recent decades, consumption of energy has grown larger due to the developing world economy, growing population and rapid urbanization, etc. According to International Energy Agency key world energy statistics, in 2010 total world final energy consumption was around 8,677 Mtoe (Million Tonnes of Oil Equivalent), twice as large as the 4,672 Mtoe it was in 1973 (IEA, 2013a). Fossil fuels are nonrenewable sources and they are currently the main source of world primary energy (Muneer, 2007; Shafiee & Topal, 2009). Conventional centralized energy systems, which generate energy in large central facilities and distribute energy through long-distance transmission, are fairly inefficient and have high environmental costs (Alanne & Saari, 2006). Furthermore, there is growing evidence indicating that accelerating climate change is closely related to human activities—particularly the combustion of fossil fuels (IPCC, 2007a). With emerging global concerns on energy supply and climate change, energy security and climate issues have frequently occupied the front pages of the news and have fostered increased research on renewable energy development, distributed generation, sustainable energy systems, and spatial energy planning.

On the path of moving towards sustainability, it is widely accepted that a transition from the prevailing centralized energy system to a decentralized, more sustainable energy system is necessary (Bazmi & Zahedi, 2011; Calvert et al., 2013; Delucchi & Jacobson, 2011; IEA, 2009).

In contrast to a centralized energy system (which generate electricity in large centralized facilities), decentralized energy systems that mainly rely on distributed generation and renewable energy are emerging as a more efficient trend in terms of sustainable energy generation and distribution (Ackermann et al., 2001; Alanne & Saari, 2006). Renewable energy development is a core element in a sustainable energy system. Renewable energy is energy that is derived from natural processes and renewable sources (e.g., sunlight and wind). Solar, wind, geothermal, hydro, and biomass are common sources of renewable energy. Since the year 2000, Renewable Energy Sources (RES) have driven much of the growth in the global clean energy sector (IEA, 2013a). A vision of a "100% renewable" power base for the global economy has been raised (Droege, 2012; Jacobson & Delucchi, 2011). A series of pioneering projects have been undertaken to explore the possibilities of realizing "100% renewable" communities, regions or even countries. Among these efforts, the island of Samsø in Denmark has established itself as a model renewable energy community by achieving the 100 percent renewable target, being powered by wind, solar and other renewable energies.

However, due to their naturally varying and diffused geographical qualities, RES capturing requires further technical and spatial considerations. Also, as cities have always relied on their hinterlands (surrounding, rural, distant places) for natural resources from water, food, fuel to waste assimilation (Geist, 2006), in the foreseeable future, the growing deployment of renewable energy will steady the city-hinterland relationship in terms of energy supply (Girardet et al., 2013). Spatial renewable energy planning is indispensable in developing a sustainable energy system.

Rooted in urban metabolism theory (Wolman,1965; Odum, 1996; Barles, 2009; Kennedy et al., 2007; Pincetl et al., 2012) and the self-sufficient cities concept (Droege, 2004; Genske et al., 2009; Schmidt, et al., 2012) and focused on a vision of energy self-sufficiency, a novel idea of exploring the feasibility of achieving regional energy self-sufficiency through the concept of the energy deficit-surplus matching is introduced in this research. It provides a new angle on energy-geography research. The proposed energy deficit-surplus matching method enables linkage of spatial modeling with assessment of regional energy consumption and renewable energy supply potential. Inspired from city-hinterland relationship in energy supply perspective, energy matching is an idea that an area that has more energy production than its own energy demand, which could in turn supply areas with energy deficits. Achieving regional energy self-sufficiency through energy deficit-surplus matching could have profound significance in ensuring global energy security and mitigating climate change.

1.2 Research Questions and Objectives

The goals of this thesis are to explore the following questions:

1. **Is the energy deficit-surplus matching approach useful in determining whether a region can reach energy self-sufficiency on an annual basis through only renewable energy supply?**
2. **How does the energy matching approach distribute areas in order to balance energy deficit and surplus within the study region?**

While answering these questions, this thesis will address four specific research objectives:

1. To provide a new approach to energy-geography research and to propose the energy deficit-surplus matching as a new concept for sustainable energy system planning.

2. To develop the proposed energy deficit-surplus matching method and the matching tool.
3. To test the energy deficit-surplus matching tool using the case of residential electricity self-sufficiency within the Province of Ontario.
4. To understand how energy matching result distribution responds to supply fraction combinations of areas of differing population density under varying supply-demand relations.

1.3 Scope & Approach

The scope of this research is to propose an energy deficit-surplus matching approach and to apply it to a case study region - the Province of Ontario, Canada - to assess the potential for residential electricity self-sufficiency. The Ontario case is a necessary simplification as inter-provincial or international power flows are too complex and not necessary for this proof-of-concept study. Also, at this stage of development, the proposed approach is focused on the consideration of renewable sources on an annual average basis and does not deal with resource and demand variability, transmission infrastructure, cost and other relevant policies and social or financial issues. In addition, only solar PV energy is considered in this research. Other sources of renewable energy such as wind, and geothermal could also be used, however this proof-of-concept study is restricted to solar PV.

1.4 Thesis Organization

This thesis comprises five chapters. Chapter 1 presents a brief introduction to the research topic, research objectives and questions. Chapter 2 provides a review of existing literature that informs this study. The review includes energy security, climate change, and sustainable energy systems. Chapter 3 describes the proposed energy deficit-surplus matching approach and methods that were employed in the research. Chapter 4 presents results and analyzes findings from the case study and other exploratory exercises. Chapter 5 reiterates major findings relevant to the research objectives and questions and provides implications and recommendations for energy planning. The contribution and limitations of the research are also discussed and future research directions are suggested.

Chapter 2 Literature Review

This chapter reviews the background information and knowledge regarding energy security and climate change issues and proposes deployment of sustainable energy systems in the upcoming future. Decentralized energy systems and renewable energy deployment are two important aspects of sustainable energy systems, based on which, urban metabolism and energy self-sufficiency, and city-hinterland relationship are explored in order to develop a novel approach: energy deficit-surplus matching as a possible solution to develop a more sustainable energy system. Figure 2.1 below shows a map of literature topics and how these topics relate to the energy matching idea.

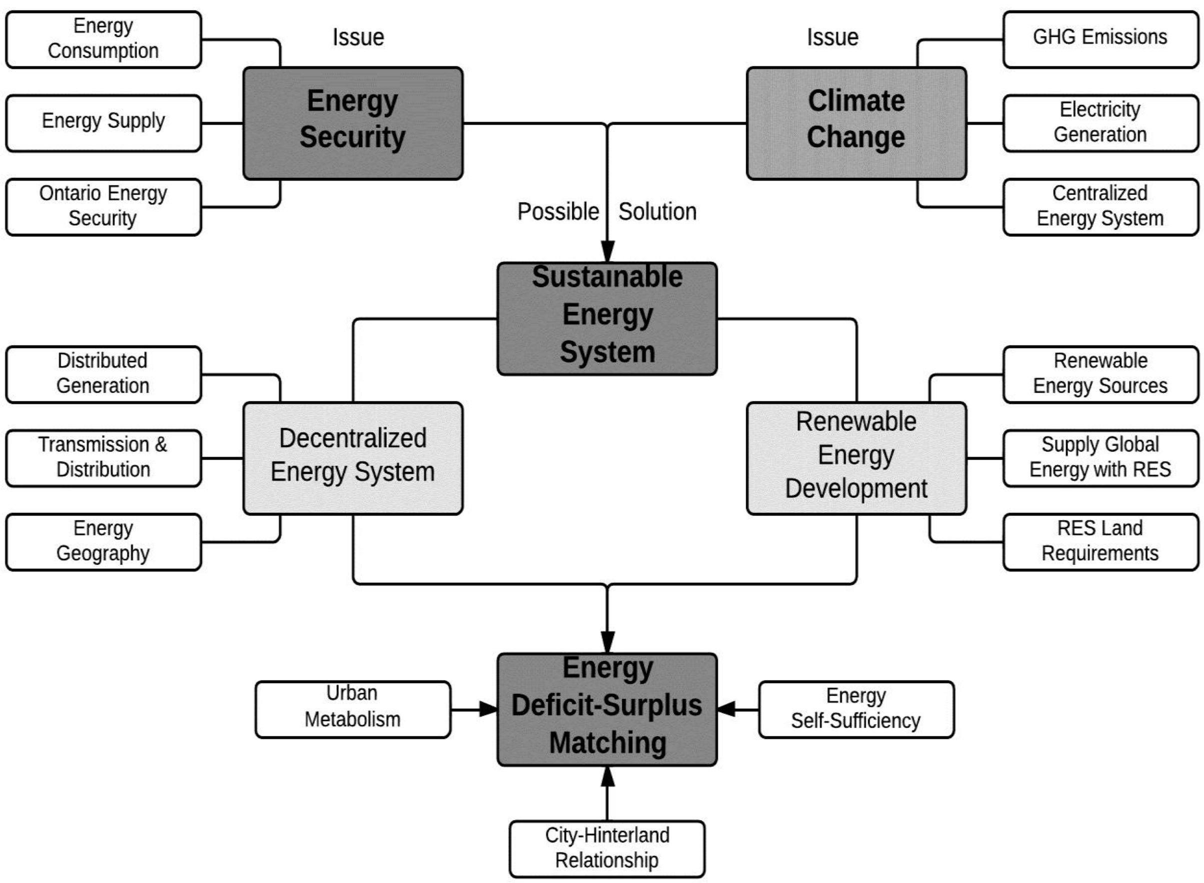

Figure 2.1: Structure of Literature Review

2.1 Energy Security

2.1.1 **What is Energy Security?**

Energy is essential to human well-being and the functioning of modern economies. Access to abundant, clean and cheap energy has become a crucial advantage among countries, because energy availability is closely linked to national security and economic development. To the contrary, uneven distribution of energy supplies could cause significant vulnerabilities and disadvantages. With the world's dependence on energy, both developed and developing countries have put energy security in a distinctive place in national security thinking.

Energy security, according to the International Energy Agency is "the uninterrupted availability of energy sources at an affordable price" (IEA, 2013b). There are two aspects of energy security: long-term and short-term energy security. Long-term energy security refers to "supplying energy in line with economic developments and environmental needs"; short-term energy security focuses on "the ability of the energy system to react promptly to sudden change in the supply-demand balance" (IEA, 2013b). Energy security discussed in this thesis covers both long-term and short-term aspects.

Strong reliance on energy makes modern societies vulnerable and they could easily face energy security threats. Several energy crises in recent history (1970s oil crisis, 2011 Japan Fukushima nuclear disaster, etc.) have caused serious economic and environmental impact, giving critical alarm for many countries. An "Energy and Security" report produced by the Australian Strategic Policy Institute summarized six types of risks for energy security: coercive manipulation of energy supplies; energy competition as a trigger for conflict; supply disruption due to political instability; attacks on supply infrastructure by transnational actors; market competition and accidents; and natural disasters (Wesley, 2007). Realizing the importance of energy security, efforts have been made around the world to improve energy security. The emergence of the OPEC cartel was a milestone that prompted some countries to evaluate and increase their energy security. In the U.S, the United States Energy Security Council has made its mission statement to reduce oil's virtual monopoly over transportation fuel and open the transportation fuel market to competition which includes more non-petroleum fuels, liquids, gas or electricity (United States Energy Security Council, 2013). The U.S. Energy Independence and Security Act (EISA) of 2007, sets Federal energy management requirements in areas such as: energy reduction goals for Federal Buildings, reducing petroleum/increasing alternative fuel use (U.S. Department of Energy, 2010). In many countries, more and more attention has been given to domestic resources, alternative oil and renewable sources. The EU, led by Germany, has made energy security a high profile public policy issue by boosting renewable energies through the famous German Renewable Energy Act. The German Renewable Energy Act (in German: Erneuerbare-Energien-Gesetz, EEG) came into force in the year of 2000, and it is designed to stimulate the development of RES to reduce Germany's energy imports (German Renewable Energies Agency, 2013). Other European countries such as Iceland and Denmark are planning to become energy-independent through deploying 100% renewable energy i.e. Iceland's hydrogen economy (Arnason & Sigfusson, 2000) and wind power development in Denmark (Aslani, Naaranoja, & Wong, 2013; Menegaki, 2013).

Among all the efforts for improving energy security, major measures include: promoting energy diversity, energy efficiency and flexibility and response to energy emergencies, reducing dependence on any one source of imported energy, reducing overall demand through energy conservation, increase energy supplies and developing renewable energy sources (Wesley, 2007). Renewable energy production from sources such as solar, geothermal, hydro, biofuel and wind are being used to meet energy demands and at the same time mitigate GHG emissions. The deployment of renewable technologies will help increase the diversity of electricity sources and contributes to the flexibility of the system; therefore improving the resilience of the energy system to shocks (IEA, 2009). Rapid development of RES would also lead to significant energy security and economic benefits. This research focuses particularly on exploring the feasibility of achieving energy self-sufficiency through renewable energy development.

2.1.2 **Energy Consumption**

The modern world relies on a vast energy supply to fuel everything from economic activities, scientific experiments, transportation, to social development. Energy consumption can be primary energy consumption or final energy consumption. Primary energy consumption is defined by OECD as “the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process.” (OECD, 2001) Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture, and it includes energy used in four major sectors: residential, commercial (includes institutional and pipelines), industrial, and transportation (IPCC, 2007b). According to IEA 2013 Key World Energy Statistics, world total final consumption from 1973 to 2011 has almost doubled from 4674 to 8918 Mtoe. A breakdown of the fuel share of total final consumption in Figure 2.2 shows that from 1973 to 2011, there was an 7.3% drop in oil’s share and a 3.6% drop in coal, while electricity consumption rose from

9.4% to 17.7% and an increased consumption of “other” sources (includes geothermal, solar, wind, heat etc.).

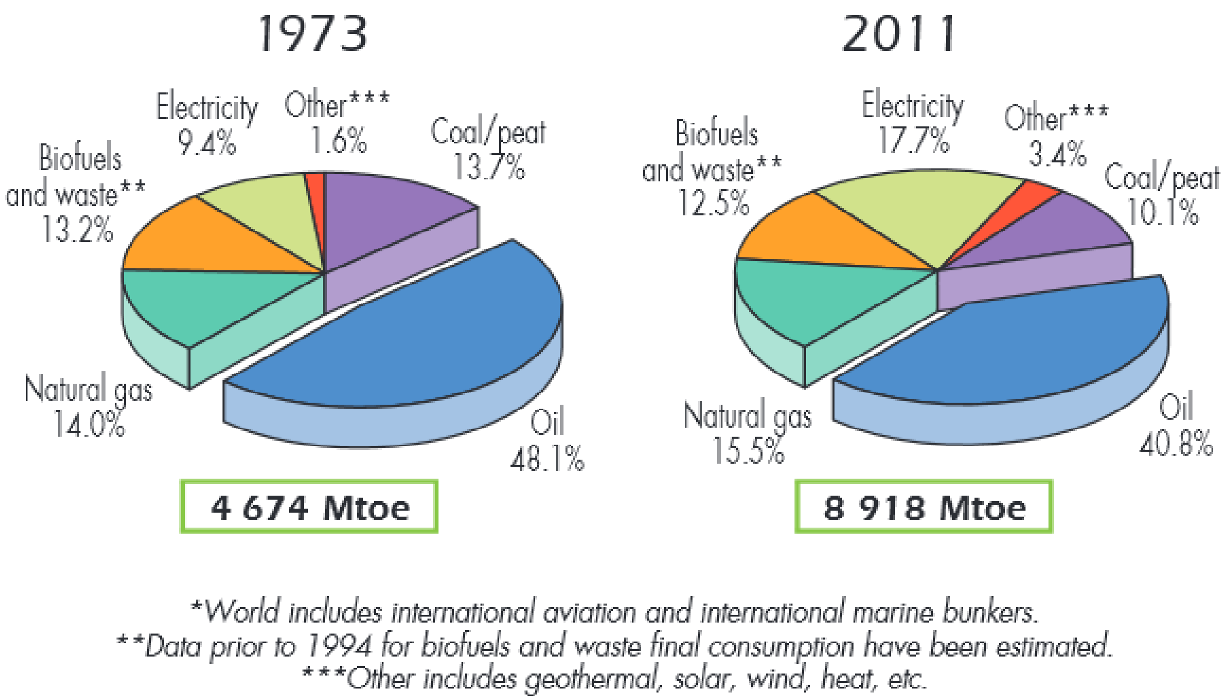

Figure 2.2: 1973 and 2011 Fuel Shares of Total Final Consumption

Source: Key World Energy Statistics 2013, (IEA, 2013a, p. 28)

Electricity is a unique and multipurpose energy carrier in the modern global economy - it can be generated from virtual all primary energy sources to provide a wide range of useful goods and services irrespective of scale (IEA, 2009). It is an essential element of technological innovation, communication, safety, supply of water, treatment of wastes, improved health, and economic growth. Most electricity is used in the residential sector because homes and apartments use electricity for lighting, appliances, electronics, and for heating and cooling (Aydinalp , Ugursal, & Fung, 2002). This paper takes electricity as main research object and focuses on residential electricity consumption and generation.

Urbanization & Energy Consumption

As one of the dominant trends of economic and social changes of the 20th century, urbanization is defined as "increase in the proportion of a population living in urban areas; and process by which a large number of people become permanently concentrated in relatively small areas, forming cities." (United Nations, 1997). Urbanization reflects three demographic trends: natural population increase, rural to urban migrations, and international migration (Rodrigue, 2013). There has been unprecedented global population growth and urbanization in recent decades (Miller & Small, 2003). In 2008, for the first time in history, more than half of the world's population lived in towns and cities; and the population living in urban areas is projected to gain 2.6 billion by 2050; urban areas will absorb all the population growth and draw some rural population in the future (United Nations, 2012).

Urbanization is a major characteristic of economic development, and it involves many structural changes throughout the economy that have important implications for energy use (Jones, 1989). The transition from a dispersed settlement to a dense settlement will have significant environmental impact (Miller & Small, 2003). Urbanization is a concentration of population and production. It involves the process of transitioning the work force from agricultural activities to industrial and service activities; it cannot be separated from industrialization. There has been an enormous increase in the demand for energy since the middle of the last century as a result of industrial development and population growth (Lu et al., 2013; Pereira & Assis, 2013). Modern cities are facilitated by industrial production, which has a great influence on energy use.

In addition, urban form also has an impact on energy consumption. Urban areas are built-up spaces of higher density and production and consumption functions that are distinct from rural or undisturbed natural areas (Droege, 2004). Many previous authors suggest that urban form (i.e., city size, density, and center distribution pattern) influences urban energy consumption (Owens, 1986 & 1992; Safirova, Houde, & Harrington, 2007; Genske et al., 2009; Lu et al., 2013; Long et al., 2013) Transportation is a key link between energy and urban form. Abundant evidence has demonstrated that increasing spatial density of economic activities and urbanization, as well as urban form increases the energy consumption on transportation (Marique et al., 2013; Long et al., 2013; Rodrigue, 2013). Energy consumption in buildings is another component that contributes to the overall urban energy consumption (Safirova, Houde, & Harrington, 2007). The building sector, mainly referring to residential and commercial buildings, encompasses a large part of the final energy consumption of developed countries (Perez-Lombard, Ortiz, & Pout, 2008). In many countries, building energy consumption is very often responsible for about 40% of the total final energy demand (Bazmi & Zahedi, 2011), which is mainly electric power.

Urban areas not only consume a large portion of total energy supply, but also generate a similar portion of total GHG emissions. According to IPCC estimates, the energy supply sector is the largest producer of anthropogenic greenhouse gas (GHG) emissions globally (IPCC, 2007a). In North America, buildings and urban infrastructure are also major contributors to GHG emissions. It is found that buildings account for 37% of the total primary energy use in Canada and roughly 30 % of the total GHG emissions (Industry Canada, 2006). As global urbanization increases, energy demand and GHG emission will be expected to grow correspondingly.

Urbanization, Energy Consumption in Canada

Canada has been experiencing growing urbanization in recent decades. Urban area is defined by Statistics Canada as: "an area with a population of at least 1,000 and with no fewer than 400 persons per square kilometer." The proportion of Canadians who live in urban areas has increased steadily since Confederation (Human Resource and Skills Development Canada, 2013). Figure 2.3 below shows the population living in urban areas (percentage of total population) from 1871 to 2011. In 2011, more than 27 million Canadians (about 81% of the total population) lived in urban areas, a reversal from over a century ago (Human Resource and Skills Development Canada, 2013). And over one third (35%) of Canada's entire population in 2011 resided in the three largest urban areas in Canada - Toronto, Vancouver, and Montréal.

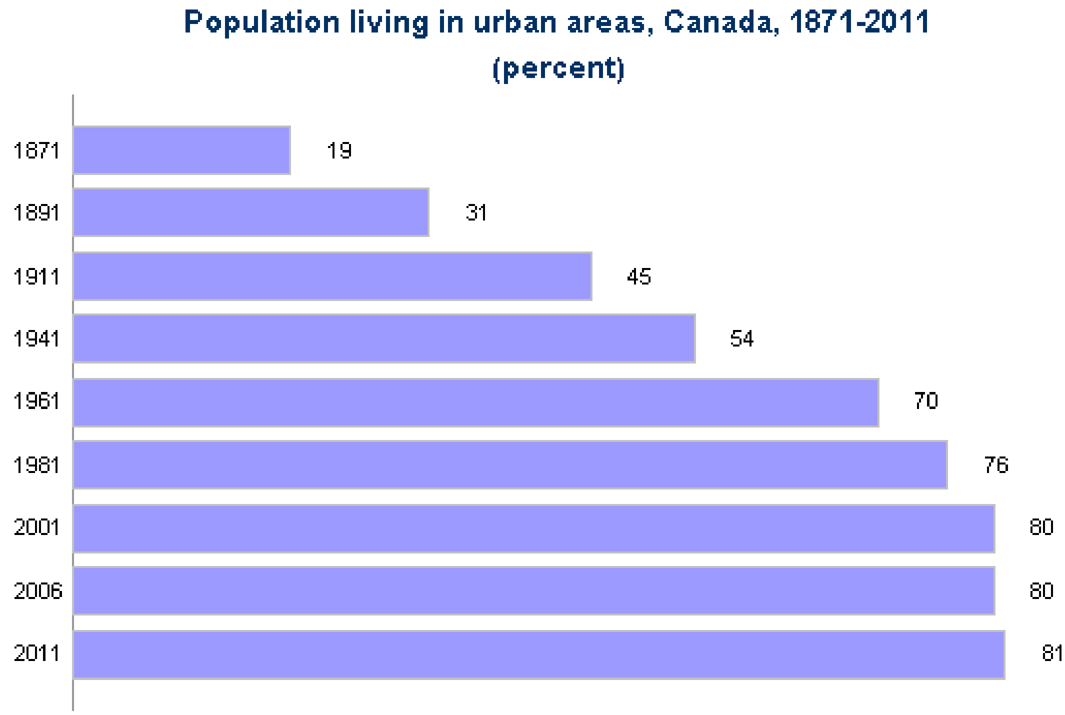

Figure 2.3: Population living in urban areas, Canada, 1871-2011

Source: Drawn from (Statistics Canada, 2011a)

Energy consumption in Canada has also grown as the urbanization increases. In 2011, Canada's energy consumption increased 3.8% to 7,945 PJ, and most energy consumed was refined petroleum product, followed by natural gas and primary electricity (Statistics Canada, 2011c). Ontario, Alberta and Quebec accounted for most of the energy consumed in Canada in 2011, combining for 73.7% of total demand (Statistics Canada, 2011c). In 2009, total electricity demand was 503.4TWh, and 31.8% of this was in the residential sector (Canadian Electricity Association, 2012).

2.1.3 **Energy Supply**

Security of the energy supply is a major component of national security and economic development. Energy supply is the delivery of energy to the point of consumption. It can be influenced by several factors including price, political and economic disputes, or physical damage to energy infrastructure.

Since human beings started large-scale burning of fossil fuels in the mid-to-late 1800s, roughly one-third of the planet's stock of fossil fuels has been consumed. Various projections from experts and researchers indicate that we are approaching peak consumption for oil (Hubbert, 1956; Owen, Inderwildi, & King, 2010). Some have asserted that the peak has already passed (Aleklett et al., 2010). According to the U.S. Energy Information Administration, there was total growth of 3.0% between 2005 and 2011 in oil supplies including crude oil production and substitutes. Between 2005 and 2011, crude oil production rose only 0.5%. It was mostly the substitutes that grew (U.S. Energy Information Administration 2013a). Net increase in global oil production is driven entirely by unconventional oil and natural gas (IEA, 2012).

Meanwhile, world electricity generation has tripled over the last three decades from 6,115 TWh in 1973 to 22,126 TWh in 2011; see Figure 2.4, which also shows the breakdown of fuel shares of generation sources. It can be seen that there's a clear decline in fossil thermal electricity generation share (coal and oil) and an increase in generation from nuclear, hydro and other renewable energy sources.

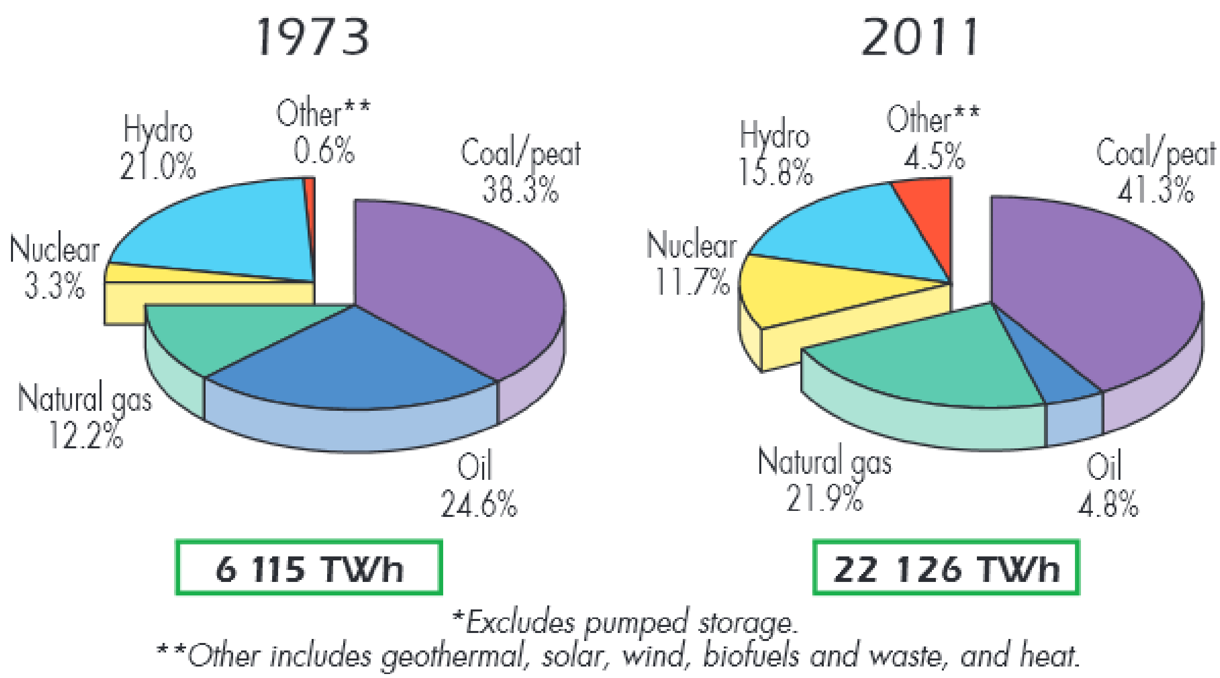

Figure 2.4: World Electricity Generation from 1973-2011 by fuel (TWh)

Source: Key World Energy Statistics 2013, (IEA, 2013a, p. 6)

In Canada, unconventional production has begun to play a larger role in the national energy supply (Statistics Canada, 2011c). Canada's significant renewable sources include wind, biomass, solar, tidal and wave. These technologies have grown rapidly in the last few years, despite the challenges on availability and cost. Policy and incentives have stimulated renewable energy generation, such as the famous Ontario feed-in-tariff that is part of the Green Energy and Green Economy Act (Green Energy Act, 2009; Yatchew & Baziliauskas, 2011). Canadian wind power capacity has experienced strong growth in recent years with a total installed capacity of 7,051 MW in 2013 by October, equivalent to about 3% of Canada's total electricity demand (Canadian Wind Energy Association, 2013).

2.1.4 **Ontario Energy Security**

In terms of energy security, Canada is in a unique position as both being an importer and exporter of energy products. The report "*Canadian Energy Security: What Does Energy Security Mean for Canada*" produced by students of the Graduate School of Public and International Affairs, University of Ottawa in collaboration with the Canadian Security Intelligence Service, identifies eight interdependent factors which together constitute Canadian energy security: energy diversity; market transparency; investment; free trade regime; energy infrastructure; energy intensity; environment; and geopolitics (University of Ottawa, 2009). The report concluded that "Canada is currently energy secure as there is no threat of sufficient magnitude to seriously alter the situation in the coming decades" (University of Ottawa, 2009, p. 31). However, in the context of globalization, Canada is deeply integrated into the global energy market, and any unforeseen disruptions, market volatility uncertainty, climate change, security threats, etc., could all negatively impact Canada's energy demand and supply. With this in mind, the efforts and study on Canada's energy security must continue. Each province should also put energy security high on its own agenda.

According to Natural Resource Canada's Energy Use database, the top three energy sources consumed in Ontario are oil, natural gas and electricity (Natural Resource Canada, 2012). Unlike the highly united European countries, which are vulnerable to interruptions of energy supply, Ontario's vast landscape offers an abundance of natural energy resources to maintain its supply. However, as globalization has made the world into one market to exchange resources and products, energy supply is no longer absolutely secure due to unstable economic conditions, and future movements in global commodity prices. Ontario could also face geopolitical risks and energy security threats; therefore, it is necessary for Ontario to understand its energy security position and develop actions to secure energy supplies. A research report on energy security for Ontario produced by Mowat Center for Policy Innovation analyzed three energy security policies on oil, natural gas and electricity (Joshi, 2012).The report states that "Ontario's security policy is minimalist for oil, being left to markets and emergency planning, but more interventionist for electricity, with self-sufficiency favored as an inherently worthwhile policy objective without reference to the costs and benefits." (Joshi, 2012, p. 5) See Table 2.1.

Table 2.1: Ontario Current Energy Security Policy

CRUDE OIL	NATURAL GAS	ELECTRICITY
Minimalist	Explicit	Interventionist
Unexamined alternatives Unknown implications	Balance costs, benefits and risks Update assumptions and plans	Self-sufficiency bias Missed opportunities

Source: "Energy Security for Ontario", Mowat Center, (Joshi, 2012, p. 4)

There are different ways to approach energy security, but the goal is the same: to reduce the risk of losing energy access and a secure energy supply. As shown above, Ontario's approach to electricity security is to plan for the electricity system to be able to meet provincial demand, because electricity is not like crude oil and natural gas that can be stored, it requires instantaneously matching supply to demand. For long-term electricity security, Ontario's Green

Energy Act was created to expand renewable energy generation from sources such as solar, wind, and hydro to secure Ontario's electricity supply. This is a start towards achieving Ontario electricity self-sufficiency through renewable generation. Self-sufficiency would help reduce electricity transmission loss and improve electricity supply security.

2.2 Climate Change

Climate change is one of today's most urgent issues, with mounting evidence indicating that climate change is very likely to be caused by anthropogenic emissions. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (IPCC, 2007b). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2007b). This section discusses the climate change issue with a particular focus on its relationship to energy.

2.2.1 GHG Emissions

Greenhouse gases (GHG) are gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emits radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds (IPCC, 2007b). Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere (IPCC, 2007b). The international scientific community has determined that human activities are a major source of these greenhouse gases. Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970s and 2004 (IPCC, 2007a). International agreements/treaties are ideally made to reduce these emissions. The Montreal Protocol deals with the halocarbons and other chlorine and bromine containing substances, to protect the ozone layer. The Kyoto Protocol to the United Nations Framework Convention on Climate Change set binding obligations to reduce emissions of CO_2, N_2O, CH_4, sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Based on IPCC Climate Change 2007 report, the United States Environmental Protection Agency (EPA) summarized global GHG emissions data by gases and sources. It found that energy supply from burning of coal, natural gas and oil is the largest single source of global greenhouse gas emissions, 26% of 2004 global GHG emissions, as seen in Figure 2.5. Reducing GHG emissions from energy supply would have a significant impact on climate change mitigation.

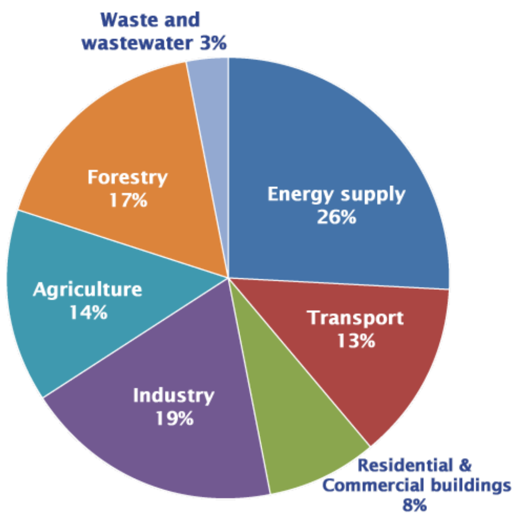

Figure 2.5: 2004 Global GHG Emissions by Source

Source: (IPCC, 2007a) based on global emissions from 2004. Details about the sources included in these estimates can be found in the Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

According to "*National Inventory report 1990-2011: Greenhouse gas Sources and Sinks*", Canada's main sources of greenhouse gas emissions by economic sector are shown in Figure 2.6. After oil and gas and transportation, electricity is in third place in contributing 13% of Canada's total GHG emissions (Environment Canada, 2013). Canada's GHG emissions from electricity generation are lower than the global averages in Fig 2.5 due to the larger role hydroelectric generation plays in Canada than in most other countries.

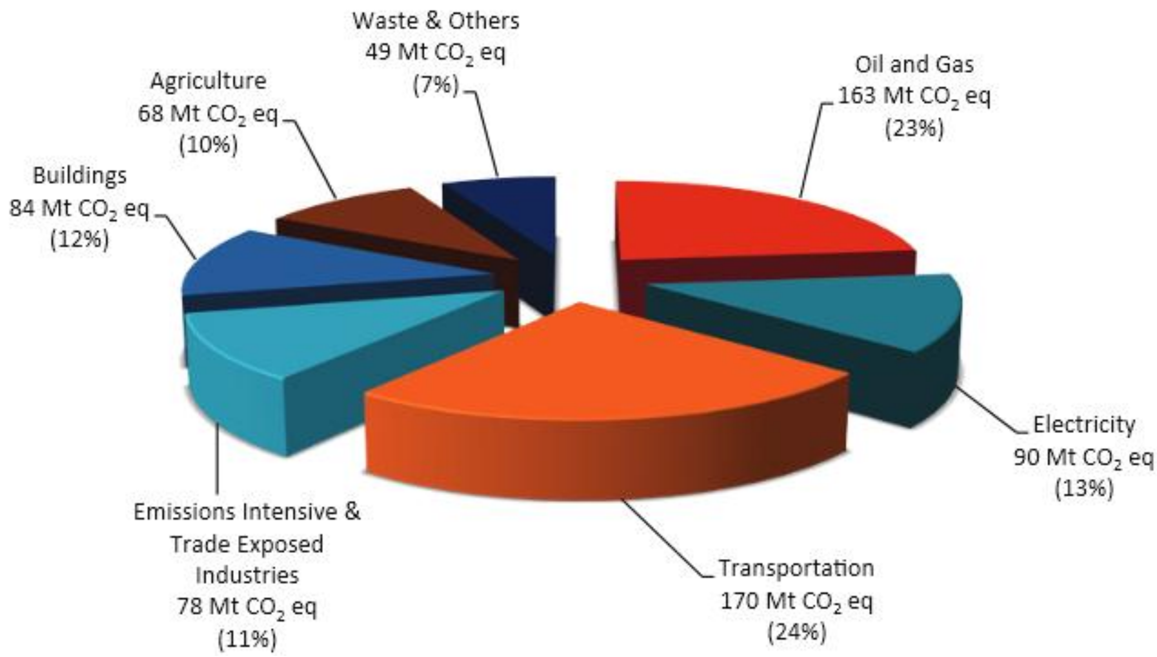

Figure 2.6: Canada's Emissions Breakdown 2011, by Economic Sector (Total = 702 Mt)

Source: National Inventory Report 1990–2011: Greenhouse Gas Sources and Sinks in Canada, (Environment Canada, 2013, p. 6)

2.2.2 Electricity Generation

Electricity was originally generated by burning fossil fuels (mostly coal) or at remote hydroelectric dams. Conventional electricity generation technologies contributed tremendously to global GHG emissions (Mallia & Lewis, 2013; Momoh et al., 2012). Lenzen reviewed the current state of development of electricity-generating technologies (Lenzen, 2010). From Table 2.2 below (adapted from Lenzen) we can see that coal is used to generate most of the electricity but with biggest environmental impact, while renewable sources (wind, solar, geothermal etc.) could generate considerable electricity with much less environmental impact. Recent years, the current electricity system is considered to be unsustainable due to concerns over urban air quality, global warming, fossil fuels shortage etc. However, because of the relatively higher generating cost of renewable technologies, conventional coal and oil sources still dominate most electricity generation.

Table 2.2: Current (2010) Electricity Generation Technologies Comparison

Technology	Annual generation (TWh_{el}/y)	Energy requirements (kWh_{th}/kWh_{el})	CO_2 emissions (g/kWh_{el})	Generating cost (US ¢/kWh)
Coal	7755	2.6-3.5	900	3-6
Oil	1096	2.6-3.5	700	3-6
Gas	3807	2-3	450	4-6
Nuclear fission	2793	0.12p	65	3-7
Large hydro	3121	0.1	45-200	4-10
Small hydro	≈250	n.a.	45	4-20
Wind	260	0.05	≈65	3-7
Solar-photovoltaic	12	0.4/1-0.8/1	40/150 – 100/200	10-20
Concentrating Solar	≈1	0.3	50-90	15-25
Geothermal	60	n.a.	20-140	6-8
Biomass	40	2.3-4.2	35-85	3-9

Source: Adapted from (Lenzen, 2010, p. 468)

According to IEA Statistics, 2010 world total power demand was 20,185 TWh with 13,306 TWh coming from fossil fuels (65.9% share of the total generation mix), 3894 TWh from all renewables (19.3%), and 2985 TWh from nuclear (14.8%). Resulting emissions are 11.4 $GtCO_2$-eq. As shown in Figure 2.2, electricity use growth (from 1973-2011) was larger than any other fuel, and this trend is expected to continue throughout the coming decades with more world population in developing countries connecting to power grids. Therefore, electricity deserves attention with regard to its contribution to global greenhouse gas emissions. There is a huge mitigation potential in the electricity-supply sector in the future if more renewable sources (e.g., hydro, wind, solar geothermal, biomass) replace fossil-fuel generation. This shift will also be promoted by improvements in energy-storage technologies, supportive policy incentives and priority grid access for renewables.

2.2.3 **Centralized Electricity System**

An electricity system is an interrelated network of electric power chains that consist of electricity production, transmission, distribution, and consumption (Kim & Dale, 2005). There are political, economic, social and technological aspects of an electricity system, yet this research only deals with it from the technological perspective.

In the 1900s, electricity was generated in large central power plants and transmitted to consumers via transmission and distribution networks. An example of a centralized energy system is shown schematically in Figure 2.7. Under the centralized energy system, electricity is generated by central power stations. Most of the central generation stations are large natural gas or coal boilers or nuclear plants that are situated remote from end-users to minimize negative impacts on humans (Momoh, Meliopoulos, & Saint, 2012). The emergence of this centralized energy paradigm is based on historical drivers that include economics of scale, innovation in electricity transmission, environmental constraints, and regulations that favor larger generation facilities (Martin, 2009).

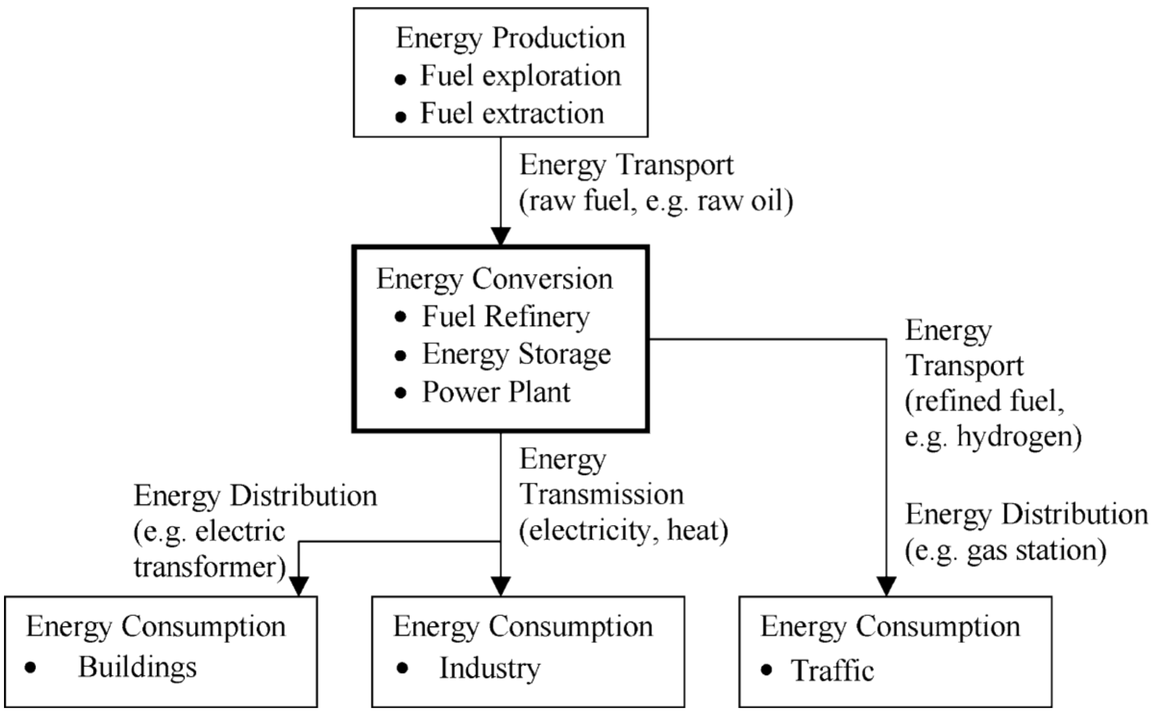

Figure 2.7: An Example of Centralized Energy System

Source: (Alanne & Saari, 2006, p. 542)

Until the 1960s, it was assumed in the power industry and governments that remote central generation was optimal, and that it would deliver power at the lowest cost versus other alternatives (Bazmi & Zahedi, 2011). However, in terms of reliability and stability under unforeseeable events, centralized energy supply system is losing its appeal for being vulnerable to failure. The Fukushima Daiichi nuclear disaster in 2010 led to reconsiderations on energy security and centralized energy systems in many countries (Mez, 2012). Apart from vulnerability and insecurity, centralized energy supply systems are losing their attractiveness due to a number of factors, including the depletion of fossil fuels, climate change impacts, insecurities affecting energy transportation infrastructure, and the desire of investors to minimize risks through the deployment of smaller-scale, modular generation and transmission systems (Ackermann et al., 2001; Alanne & Saari, 2006; Martin, 2009).

2.3 Sustainable Electricity System

Under the concept of sustainable development, with concerns over urban air quality, global warming, and dependence on depleting fossil fuel reserves, a transition to a more sustainable electricity system is seen to be necessary. A sustainable electricity system is a system with the ability to meet everybody’s needs at an affordable price and to supply clean, safe, and reliable electricity (Bonser, 2002). A transition from the current system to a more sustainable electricity system involves three aspects. First, meet the growing demand with more sustainable electricity, which calls for more renewable energy sources. Second, transmit and distribute electricity with greater efficiency, which calls for more localized energy generation. Third, spatial planning decisions about land and infrastructure development largely determine not only the energy demand of cities and regions, but also the potential to supply areas from renewable energy sources. All three aspects are important to achieve regional energy self-sufficiency and a more sustainable electricity system.

2.3.1 Decentralized Energy System

In contrast to large, centralized power plants, small-scale decentralized generation units, which use multiple energy sources and are situated close to energy consumers, are emerging as a viable alternative (Alanne & Saari, 2006). A decentralized energy system is an efficient, reliable and environmentally friendly alternative to the traditional energy system. Unlike centralized energy generation, a decentralized energy system is characterized by locating energy production facilities closer to the site of energy consumption (Martin, 2009) and is designed to accommodate renewable energy sources as well as combined heat and power to reduce fossil fuel use and increase efficiency. An example of decentralized energy generation is a building equipped with solar heating and a solar PV electricity supply and electricity storage. Figure 2.8 is a schematic illustration of decentralized energy system (Alanne & Saari, 2006).

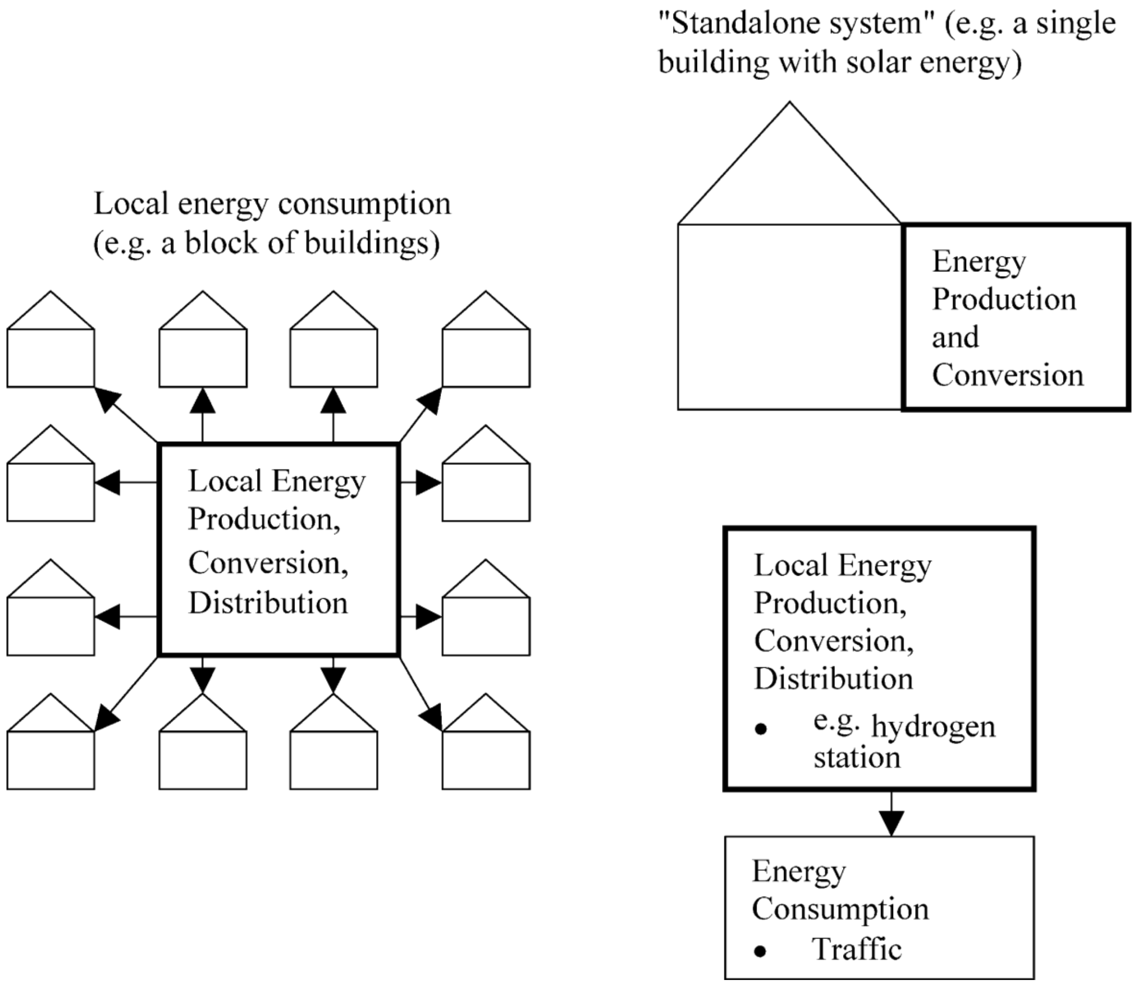

Figure 2.8: An Example of Decentralized Energy System

Source: (Alanne & Saari, 2006, p. 543)

Distributed Generation

The core component of a decentralized energy system is distributed generation, also known as on-site generation, dispersed generation, or decentralized generation (Momoh, Meliopoulos, & Saint, 2012). “Distributed generation is an electric power source connected directly to the distribution networks or on the consumer side of the meter.” (Ackermann, Andersson, & Soder, 2001) Distributed generation uses more local resources of renewable energy such as wind, solar and biomass, and is much more easily implemented in rural areas, and in developing and emerging countries. Also, as end users are spread across a region, so sourcing energy generation in a decentralized manner can potentially reduce the transmission and distribution inefficiencies and related economic and environmental costs. In addition, establishing local generation and a local network may be cheaper, easier and faster than extending the central-station network to remote areas (Ackermann et al., 2001). Table 2.3 (from Momoh et al., 2012) compares centralized and distributed generation from several perspectives. It can be seen that a distributed system is more resilient and sustainable in terms of efficiency and environmental impact as well as ability to be sustainable.

Table 2.3: Comparison of CG and DG

Value	Centralized Generation	Distributed Generation
Continuous Power	Through operated to provide continuous power, its characteristics results in: • Low electric efficiency as a result of high losses at the transmission system • High emissions	Operated to allow a facility to generate some or all of its power on a relatively continuous basis. Important DG characteristics for continuous power include: • High electric efficiency • Low emissions
Premium Power	Provision of power at low reliability and power quality cannot be guaranteed due to inherent high power losses.	It provides electricity service at a high level of reliability and power quality than typically available from the grid.
Cost	High variable cost High maintenance costs	Low variable cost Low maintenance costs
Resiliency	Less resilient but serve high power demands continuously.	More resilient since it serves low power demands continuously.
Transmission	High voltage transmission is mandatory High losses and transmission failure	Only distribution required Reduced capital cost
Sustainability	Sources of power results in less sustainability	Sources of power makes it more sustainable

Source: Adapted from (Momoh, Meliopoulos, & Saint, 2012, p. 5)

One example of distributed generation is community energy. Community energy is a smaller scale system that includes both sustainability and community perspectives in the planning process and also makes the most of efficient use of energy by matching supplies to energy services instantaneously , taking supplies, transmission & distribution, and demand into account (Church Ken, 2007). Community energy has long been seen as a way of implementing a decentralized energy system, emphasizing energy self-sufficiency and local determination (Walker, 2008) utilizing local resources in a flexible, reliable, and environmentally conscious way.

As Alanne & Saari (2006) concluded, “A distributed energy system is a good option with respect to sustainable development in the long run,” yet there are significant technical, economic, regulatory and environmental obstacles to overcome. First of all, technical constraints such as generation capacity, voltage, security, planning, transmission and distribution need to be carefully considered. It calls for more R&D on emerging technologies, such as smart grid, energy storage, and demand response technologies. Second, from an economic perspective, distributed generation will have to lower the cost per kWh in order to be cost competitive with centralized generation. Third, significant work needs to be undertaken to alter the regulatory environment to support distributed generation such as, transforming the market (making energy market competitive by adding more RES), and providing incentives (e.g. feed-in tariff in Germany and Ontario). Last but not least, distributed generation is not guaranteed to be the cleanest and most efficient generation. The climate change impact of any system needs to be estimated and considered in the planning process. In summary, the paradigm shift from centralized electricity system to the decentralized electricity system has begun. More R&D and policy support will help accelerate the transition to a more sustainable electricity system.

Transmission & Distribution

Transmission and distribution (T&D) is crucial in any electricity system as all the energy generated needs to be shipped to the point of end-use. T&D is one of the most significant issues in centralized electricity system for both economic and technical reasons. The cost of T&D includes the cost of building transmission networks and the energy losses during transmission. A transmission network is “a system of transmission or distribution lines so cross-connected and operated as to permit multiple power supply to any principal point” (U.S. Energy Information Administration, 2013b). The cost of building transmission networks varies and it largely depends on, for example, the length of the transmission lines, geography of the terrain, population density along the route (urban versus rural) geotechnical conditions, type of construction (underground versus overhead), voltage levels, number of circuits, environmental requirements (Alberta Electricity System Operator, 2013). A high voltage DC (HVDC) line is most appropriate to transmit power over long distances with few or no intermediate connections. The Australian Energy Market Operator (AEMO) estimates the cost of HVDC transmission line per km as shown in Table 2.4, which ranges from 1.49-3.12 Million Australian dollars (AUD) (1AUD=1.0389 Canadian Dollars, 2012 average) per km.

Table 2.4: Cost Estimates of HVDC Transmission Lines

Plant	Cost estimate ($M per km)
±150kV 352 MW bipole submarine cable	1.57
±300kV 704 MW bipole submarine cable	1.64
±300kV 1306 MW bipole submarine cable	3.12
±300kV 770 MW bipole on-shore cable	1.49
±300kV 1253 MW bipole on-shore cable	2.18

Source: (Austrelian Energy Market Operator, 2012, p. 6)

T&D losses include losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage (The World Bank, 2013). T&D loss costs account for up to 30% of the cost of delivered electricity on average (Martin, 2009). According to EIA data, U.S. annual electricity T&D losses average about 7% of the electricity that is transmitted. The average world T&D losses are 8.6% of the total electric power output, while the average Canada T&D losses are 7.4% of the output, which means around 7.4% of total electric power output in Canada was lost, which is equivalent to around 40,000 GWh of electricity. In the residential sector, the retail prices of electricity in large Canadian cities range from 6.76-15.01 cents/kWh before tax (Hydro-Québec, 2012, p. 20). Using these costs, 40,000

GWh implies a cost due to T&D losses of at least $2.7 Billion CAD. In addition to the financial cost, these electricity losses also have an associated cost in terms of GHG emissions. Thus, reducing T&D losses is a goal in developing any type of electricity system.

Distributed generation is superior to centralized generation in terms of T&D losses, as one of the key characteristics of distributed generation systems is proximity to the end consumer, where electricity is produced at or close to the end use. Distributed generation requires less T&D infrastructure to deliver generated electricity to end users than centralized generation. Therefore, promoting distributed energy systems would save T&D losses and reduce infrastructure requirements for both financial and environmental reasons.

Energy Geography

Looking back in human history, development has a great connection with energy development since the first fire was made. Every big step in human history was supported by technological progress in energy development. Geography is central to understanding and addressing any energy-related issues: energy production, distribution, energy consumption etc. (Pasqualetti, 2011). "New geographies of energy" is rising as a new energy research topic to examine the changing energy landscape.

In their recent publication *Sustainable Energy Landscapes - designing, planning and development*, Stremke & Dobbelsteen reviewed the four stages of energy landscape within the context of four major economic stages: organic economy, the mineral economy, the electric economy and the sustainable economy (Stremke & Dobbelsteen, 2012). Back 100,000 years, the energy landscape was minor with small population and the energy source was mainly wood, solar, and wind. The industrial revolution was a threshold when people started relying on mineral resources instead of organic and renewable resources. As fossil fuel became more available, the human impact on landscapes became more destructive. Those mineral resources are coal, oil and natural gas. The energy landscapes of coal, oil, and natural gas recovery and transport have been expanding for centuries. Around the 1930s, energy landscapes of the electricity economy appeared, and the generation and transmission of electricity have produced the most visible energy landscapes on the planet. Power plants and transmission lines gradually shape new energy landscapes and are integrated with urban infrastructure. Today, while we are seeking the post-carbon era, a new sustainable economy is appearing to influence the energy landscape with the renewable sources wind, water, solar, geothermal, and biomass (Stremke & Dobbelsteen, 2012).

Energy landscapes result from a natural human need for energy; they also reflect political imperatives, public reactions, and historical events, growing population density, and Earth's natural limits. Understanding energy landscapes gives us a good knowledge of the role of energy in changing human history and the development path from organic economy to sustainable economy.

On the other hand, it is understood that the transition from conventional to decentralized sustainable electricity system will have impact on the landscape. In the past, most conventional energy facilities are far away from cities; and large wind/solar farms, hydro dams and bio-energy plants are also locating in more remote rural areas. Under a decentralized energy system, in order to keep the proximity of energy source with end-uses, energy generation needs to be situated close to the point of use, which presents both challenges and opportunities with respect to energy and urban planning.

It is urgent to link renewable energy production with sustainable urban development. In essence, a city can influence the implementation of renewable energy systems with planning considerations, such as incorporating renewable systems into the overall design of new developments or solar access by-laws. Many spaces within existing urban environments, such as roofs and façades, can be utilized for renewable energy production. By fully mapping the potential of the city-its physical capacity to generate renewable energy based on the interaction of its built form with renewable resources, the goal is an energy autonomous city that maximizes its potential for energy generation within its urban boundaries (Genske, Porsche, & Ruff, 2009). A strategy of developing an energy mix from renewable urban thermal and electrical resources would aim at maximizing the local supply to meet urban energy needs.

2.3.2 Renewable Energy Development

Renewable sources of energy have been the driver of much of the growth in the global clean energy sector since 2000. Worldwide renewable electricity generation since 1990 grew an average of 2.8% per year (IEA, 2012). In 2009, renewable energy supplied an estimated 16% of global final energy consumption. Krewitt et al. (2007) projected 70% of electricity and 65% of global heat supply will come from renewables in 2050. However, despite the inspiring statistics showing the growing share of renewables in world energy supply, in reality, renewables still play a minor role in urban redevelopment. Transforming the current fossil energy system to a renewable energy supply is essential and feasible with enough efforts (Delucchi & Jacobson, 2011; Girardet et al., 2013). The integration of Renewable Energy Source (RES) will drive fundamental changes to social and physical energy landscapes in various ways. Increasing RES in the current energy mix will not only secure energy supply, and mitigate climate change, but also provide benefits such as job creation, increased energy security, and improved human health (Arnette & Zobel, 2012).

Renewable Energy Sources (RES)

Renewable energy is energy that is derived from natural processes (e.g., sunlight and wind). Solar, wind, geothermal, hydro, and biomass are common sources of renewable energy. Solar photovoltaic (PV) cells directly convert solar energy into electricity using a semiconductor material. Wind energy is kinetic energy of wind exploited for electricity generation in wind turbines. Geothermal energy is stored in rock and in trapped vapour or liquids, such as water or brines, which can be used for generating electricity and for providing heat and cooling. Hydropower is the electrical energy derived from turbines being driven by falling and flowing water in rivers, with or without man-made dams forming reservoirs. Hydropower is the world's largest source of renewable electricity. Bioenergy is energy derived from the conversion of biomass where biomass may be used directly as fuel, or processed into liquid and gaseous fuels.

Although RES have massive energy potential, they are generally diffuse and not fully captured, most of them are variable in time, and have distinct regional variability. According to Calvert et al., the ability to realize RES potential is constrained by a range of geographic factors related to resource potential, the distribution of resources, land availability/suitability, the absorptive capacity of proximal infrastructure, and local socio-political acceptance (Calvert, Pearce, & Mabee, 2013).

With its large area and diversified geography, Canada has substantial RES that can be used to produce energy. Canada is a world leader in the production and use of energy from RES, which currently provides about 16% of Canada's total primary energy supply (Natural Resource Canada, 2012). As renewable energy development can reduce the environmental impacts of energy consumption and improve the local economy, and can increase community participation in local environmental management, a great deal of research has been devoted to different techniques focused specifically on improving renewable energy planning at the regional level (Bazmi & Zahedi, 2011; Arnette & Zobel, 2012; Calvert, Pearce, & Mabee, 2013; Genske et al., 2009; IEA, 2009; Ramachandra & Shruthi, 2007)

In order to identify an economically optimal or socially acceptable mix of RES in a region, appropriate technologies to access these materials and ideal sites for deployment are structured by local geographical nuances. One of the clearest ways to visualize connections between geography and energy is through maps. Maps show where the gas pipelines are and where the great potential for various renewable energy sources are and helps locate energy activities. Renewable Energy Potential mapping as a method has been developed to support spatial planning, because locally available RES are mapped to steer developments where they are most effective in terms of the energy system. Pasqualetti points out that in mapping renewable energy potential, realizing what roofs and open spaces are available for renewable electricity and thermal energy conversion is essential (Pasqualetti, 2011). Also, the spatial mapping of availability and demand of renewable energy sources would help in integrated regional energy planning through an energy supply-demand matching process (Ramachandra & Shruthi, 2007).

Generating a full picture of energy streams (sources and sinks) can help build a foundation for a sensible regional energy strategy (Droege, 2010).

Supply Global Energy with RES

With growing development of RES, a wave of hope rises in believing that renewable energy could supply all of the world energy demand in the future. Many have foreseen a 100% renewable world. "100% renewable" means an entirely renewable energy base for the global economy from the primary production to the final consumption of energy (Droege, 2012). In his book "*100% Renewable—Energy Autonomy in Action*" Droege collected a series of pioneering efforts ranging from initiatives of communities, regions and countries (Droege, 2012). The renewable energy island of Samsø in Denmark has established itself as a model renewable energy community by using RES to meet 100 percent of electricity demand. Samsø is a Danish island with 4,300 inhabitants, where the transition started in 1997 when 21 wind turbines were built by the islanders. Currently, 100% of Samsø's electricity comes from wind power and 75% of its heat comes from solar power and biomass energy (CBS, 2009). It also sells its surplus electricity to the mainland.

However, some argue that Samsø is a special case as an island with a low population density and mainly agricultural economy, while supplying global energy with all RES still seems to be an impossible dream in anything but the very long term. Some also claim that uncertainties in the limits of renewable resources, weather events, energy storage technologies, embodied energy cost, and variability of investments will prevent us from achieving global 100% renewable energy (Trainer, 2012). Jacobson & Delucchi explored the feasibility of providing worldwide energy for all purposes (electric power, transportation heating/cooling, etc.) from wind, water, and sunlight (WWS) (Jacobson & Delucchi, 2011). Jacobson evaluated several long-term energy systems according to environmental and other criteria and found WWS system to be superior to nuclear, fossil fuel, and biofuel systems (Jacobson, 2009). In their two publications, Jacobson & Delucchi examined WWS energy system characteristics, current and future energy demand, availability of WWS resources, area and material requirements, variability, economics and policy of WWS energy systems. They concluded that it is primarily social and political barriers, not technological and economic barriers in the way of the transition to worldwide WWS energy (Delucchi & Jacobson, 2011; Jacobson & Delucchi, 2011). It is also suggested by Delucchi and Jacobson that producing all new energy with WWS by 2030 and replacing existing energy mix by 2050 with WWS is possible.

RES and Land Use

Land use plays a significant role in development of RES, due to spatial characteristics of RES. Land use is “the total of arrangements, activities, and inputs that people undertake in a certain land cover type.” (FAO, 1997; FAO/UNEP, 1999) It is very often confused with “land cover”, which is “the observed physical and biological cover of the earth’s land, as vegetation or man-made features” (FAO, 2002). Moving towards a renewable energy future, there is no doubt that the changing energy revolution, consisting of assimilation, conversion, storage, and transport of renewable energy, will be one of the most important land uses of the 21th century, and will have a huge influence on the landscape.

There is an argument that, because the energetic density of solar, wind, water and biomass is lower than that of fossil fuel, much larger areas must be allocated to renewable energy, thus requiring substantial land resources in comparison to conventional energy sources (Fthenakis &

Kim, 2009). For example, Gagnon et al. estimated land use as 45 km^2/TWh for the PV-fuel cycle compared to 4 km^2/TWh for the coal-fuel cycle (Gagnon, Belanger, & Uchiyama, 2002). The International Energy Agency reported that renewable energy requires 7-17 times more land than conventional energy per unit of electricity per year (IEA, 2000). Others argue that the land use of renewable-energy sources, like PV, wind, and biomass, pose distinct differences from conventional fuel cycles in that they use land statically. Once the infrastructure of renewable-energy technologies is constructed, there is no need for further extraction of resources. Moreover, PV and wind power plants can be located on low quality lands (e.g., brownfields), and can often be used for multiple purposes (e.g. grazing, power generation and shading) (Fthenakis & Kim, 2009; Denholm & Margolis, 2008).

Efforts have been made to understand solar land use estimates from the literature (Horner & Clark, 2013). Fthenakis & Kim presented the normalized land requirements during the life cycles of conventional and renewable energy options, covering coal, natural gas, nuclear, hydroelectric, photovoltaic, wind and biomass (Fthenakis & Kim, 2009). They compared the land transformation and occupation matrices within a life-cycle framework across those fuel cycles. They review and update the land-transformation metric for conventional- and renewable-fuel cycles for generating electricity and conclude that the PV life cycle of power plants in the U.S. Southwest involves less disturbance of land than do conventional and other renewable-fuel cycles (Fthenakis & Kim, 2009). All in all, the emergence of more renewables energy land use will affect the appearance and spatial organization of the larger physical environment across the world, including both urban and rural landscapes.

2.4 Energy Deficit-Surplus Matching

2.4.1 **Urban Metabolism & Self-sufficient Cities**

As mentioned in Section 2.1.2 that more than half of the world's people live in cities and urban areas. The vast urban populations consume a majority of the world's resources contributing to environmental degradation locally, regionally, and globally (Kennedy et al., 2012). Increasing urbanization along with intense energy demands of modern economies have driven a rising number of research and attention on sustainable urban system, with focus on the integration of energy infrastructures, people, and natural systems in the pursuit of sustainable cities (Brabec & Lewis, 2002; Kennedy et al., 2012). The integrated study of energy and urban systems has recently become a critical component of sustainability research.

Emerged in the late twentieth century, Urban Metabolism (UM) is a systems-based approach to understand urban trajectories of resource use, waste production, and associated impacts on the environment (Wolman,1965; Odum, 1996; Barles, 2009; Kennedy, Cuddihy, & Engel-Yan, 2007; Pincetl et al., 2012). Urban metabolism is "the sum total of the technical and socio-economic process that occur in cities, resulting in growth, production of energy and elimination of waste" (Kennedy, Cuddihy, & Engel-Yan, 2007, p. 44). It provides a holistic viewpoint to encompass all of the activities of a city in a single model.

In an urban context, sustainable development can be understood as "development without increase in the throughput of material and energy beyond the biosphere's capacity for regeneration and waste assimilation (Goodland & Daly, 1996, p. 1013). Given this definition, a sustainable city is an urban region for which the inflows of materials and energy and the disposal of wastes do not exceed the capacity of its hinterlands (Kennedy et al., 2007). The idea of self-sufficient cities has been raised up to encourage a quick switch our energy supplies to renewable energy, not only to power urban infrastructures, but to power urban transport systems and daily way of life (Girardet, 2012). One important characteristic of self-sufficient city is renewable energy supply. In a self-sufficient city, renewable energy technologies should play the primary role in meeting the energy consumption needs of its residents. Cities and towns could become facilitators of change in the energy sector and have a great potential to become energy self-sufficient (Agudelo-Vera et al., 2012). Appendix I illustrates a possible future urban layout with different alternative renewable energy technologies embedded as energy supply.

2.4.2 Energy Self-Sufficiency

The desire for self-sufficiency has been a common trait of human society. The Oxford English Dictionary defines self-sufficient as ‘‘able to provide enough of a commodity (as food, oil) to supply one's own needs, without obtaining goods from elsewhere; self-reliant, self-supporting, independent’ (OED, 2013). Applied to an energy region, energy self-sufficiency means that the region's entire energy demand is produced locally, and energy deficits in one area are offset by energy surpluses in other areas within the region (Abegg, 2011).

The pursuit of energy self-sufficiency has become an important policy driver in countries which wish to eliminate energy dependency and increase national energy security (Wesley, 2007; Abegg, 2011; Joshi, 2012). This is because energy self-sufficiency could generate considerable benefits. *Environmentally*, it would help with protecting the climate and the environment. Under a centralized energy system, production and transportation of fossil fuels have caused serious environmental impacts, whereas energy self-sufficiency implies a form of the decentralized energy system that produces energy locally, decreasing transportation distances of energy resources, thus reducing energy transmission and distribution cost and risk (Alanne & Saari, 2006). Furthermore, renewable energy self-sufficiency often requires utilizing more renewable energy sources (Joshi, 2012). Together, with more renewable energy as well as reduced transportation, renewable energy self-sufficiency could significantly reduce global GHG emissions, and contribute to sustainable development. *Economically*, since fossil fuels are commodities, global energy prices fluctuate. Energy self-sufficiency with a high degree of local energy production could result in more stable energy prices (Wesley, 2007; Abegg, 2011). In addition, the development of renewable energy self-sufficiency has positive impact on creation of new green jobs and the stimulation of the local economy (Lechner, Schelepa, & Wetzel, 2013; Simas & Pacca, 2013). *Socially*, renewable energy self-sufficiency not only improves local/regional energy security, but also strengthens the local control of energy production, which gives all stakeholders a stronger local identity and motivates advancement of more renewable energy self-sufficiency within the region (Denis & Parker, 2009; Wang, Green, & Davis, 2011).

However, from a geopolitical perspective, renewable energy self-sufficiency is still arguable in terms of reliable energy supply and affordable prices. According to neoclassical trade theory, restrictions in extra-regional (energy) trade lead to lower efficiency due to foregone benefits from comparative cost advantages in other regions (Schmidt, et al., 2012). Some believe that only a global energy trading system can bring reliable and affordable energy to every nation. Nevertheless, it is believed in this research that renewable energy self-sufficiency is good for the environment and sustainable development. This research will not debate the benefits of self-sufficiency, but focuses more on the feasibility of achieving energy self-sufficiency as a logical consequence of the shift to distributed renewables that has already begun.

Renewable energy self-sufficiency can be found at different scales. There are energy self-sufficient cities, towns, and communities. Even the possibility of entire countries being energy self-sufficient is conceivable (Abegg, 2011). Pioneering areas including Güssing in Austria's Southern Burgenland, the German bioenergy village of Jühnde, and the Danish island of Samsø are leading the way towards energy self-sufficiency.

Achieving renewable energy self-sufficiency requires that energy supply-demand balance be carefully considered. Energy supply-demand relations in a certain space reflect the relations of energy production and consumption, but how to balance energy deficits and surpluses within a certain space is an important subject in energy geography. Considering energy use and supply per unit of land area is not a new idea. In 1999, Sorensen and Meibom described a model that makes the match of power demand with renewable energy supply on an area basis in a geographical information system (GIS) which helps directly identifying any mismatch entailing needs for energy trade and establishment of energy infrastructures (Sorensen & Meibom, 1999). This idea is suited for dealing with dispersed energy sources such as renewable energy. Once the energy demand and potential renewable production are determined on an area basis, it is possible to assess the ability of a renewable energy system to match demand. It can be determined if there is enough renewable energy to cover all demands or if other sources must be employed.

Nevertheless, according to the Saxony's energy agency, "an energy self-sufficient region exploits as far as possible the potentials for saving energy and increasing energy efficiency and meets the remaining average annual energy requirement in purely mathematical terms from regional sources of renewable energy (CIPRA, 2010, p. 7). This definition highlights one important point: Energy self-sufficiency is not practical without energy saving and an improvement in energy efficiency. Energy conservation which includes increasing energy efficiency and demand reduction is vital in achieving energy self-sufficiency. After all, energy that is not consumed does not need to be generated (Abegg, 2011).

Until now, numerous studies on regional or countrywide renewable energy potentials have been published (Ramachandra & Shruthi, 2007; Bazmi & Zahedi, 2011; Jacobson & Delucchi, 2011; Agudelo-Vera et al., 2012; Arnette & Zobel, 2012; Aslani et al., 2013; Stremke & Dobbelsteen 2012), but few publications present and discuss a possible detailed approach to achieving energy self-efficiency at different scales. This thesis proposes an approach with methods for exploring the feasibility of achieving energy self-sufficiency from renewable energy generation.

2.4.3 **City-Hinterland Relationship**

The idea of matching energy surplus areas with energy deficit areas within the region is inspired by the relations between a city core and its hinterlands in models of urban development. "Hinterland" typically is a rural area or region surrounding the urbanized area of larger cities or agglomerations, characterized by a less dense population and infrastructure. Usually, there are strong linkages and interdependencies between a city core and its hinterlands. Cities have always relied on their hinterlands for natural resources such as water, food, fuel, as well as waste assimilation (Geist, 2006). City-hinterland relationships cover the whole range of economic and social functions: residence, manufacturing, distribution (wholesale, retail), recreation, communication and transportation within the metropolitan complex (Epstein, 1969). The vitality of cities depends on spatial relationships with surrounding hinterlands and global resource webs (Kennedy et al., 2012). In larger cities, only a portion of the total energy demand is likely to be met by renewable energy projects located within the city boundary. To make the further expansion of renewable energies as compatible with the given area and as conflict-free as possible, describing a proper energy deficit-surplus matching flow for metropolitan or large urban centers is a significant applied outcome.

As mentioned in previous sections, the urban environment has potential to utilize its vacant space, urban brownfields and unused spaces to develop renewable energy production aiming to at least partially meet urban energy needs. Needs that can’t be met locally will need to be met with generation in the energy surplus areas – areas with more energy supply than needed to meet their own energy demand. The energy supplier is not limited to urban surroundings or remote rural areas, although smaller, rural communities are more likely to generate excess renewable energy to supply to large cities and other parts of the economy.

There are three main characteristics of an energy supplier (energy surplus area). First, the energy supplier must have surplus energy supply. Areas with insufficient energy supply to meet their own demand cannot be an energy supplier for other areas. Second, an energy supplier in this research is not limited by proximity: it does not need to be adjacent to an area with insufficient energy supply (energy deficit areas). Third, the idea of energy deficit-surplus areas matching is not limited to a particular scale. It can theoretically be applied at any scale, no matter, a city, a town, a district, a region or a country. For instance, if a city wants to achieve self-sufficiency within its own boundary, then it needs to identify energy suppliers within its boundary. Taking an urban area as an example, urban open spaces such as brownfields, vacant lots and reserve areas can be energy suppliers. There is no optimal scale for applying the energy deficit-surplus matching, but factors such as policies and geographical characteristics influence the choice of appropriate scale for any investigation.

Ideally, matching energy deficit and surplus areas would help in achieving energy self-sufficiency for cities, towns, regions, countries, or any applicable spatial unit. However, there are potential obstacles to technically realizing energy self-sufficiency. The first expected obstacle is technological barriers, such as access to transmission lines. As transmission lines are not available everywhere geographically, energy surplus areas distant from transmission lines would not be able to get connected to the supply network easily. Another potential barrier to energy matching is the policy obstacle. Energy suppliers cannot avoid dealing with political and planning considerations, as they are part of a larger, centrally overseen network. Governments and the public might have resistance in developing energy suppliers due to political, health, financial or social concerns. This thesis does not deal with these obstacles, but takes an exploratory approach to provide evidence and analysis to illustrate the feasibility of achieving regional energy self-sufficiency. These obstacles could be considered in future extensions of the current work.

Chapter 3 Methods

Chapter 3 proposes an energy deficit-surplus matching approach and illustrates how the methods are applied to a case study. This chapter is structured as follows: Section 3.1 explains the proposed approach and procedures in general. Section 3.2 shows the application of the method to the Ontario context and describes the developed energy deficit-surplus matching tool. Section 3.3 summarizes the chapter.

3.1 Research Method

Energy deficit-surplus matching begins by selecting a study region and dividing the region into smaller sub-regions, called areas here. This is done through a Geographic Information System: ArcGIS software in this research. Next the energy supply and demand are measured or estimated for each area to identify energy deficit (supply < demand) and surplus (supply > demand) areas. Once these areas are identified, a rule-based process is used to match the energy deficit areas with the surplus areas within the region in order to satisfy estimated demand. The last step is to import the matching results to ArcGIS for map generation and visualization.

Figure 3.1 shows the high-level 4-step procedure to match energy deficits and surplus areas within a study region. The procedure starts with selecting the study region. As stated in Chapter 2, energy self-sufficiency can be realized on different scales, such as cities, towns, communities or even countries, so the study region can be any appropriate scale, data permitting. After having selected a study region, an appropriate number of sub areas needs to be defined. These are usually determined by the spatial units for which data are collected or available such as blocks, neighborhoods, towns, cities, districts, etc. This can be problematic due to data availability and consistency, as each area must have the required information (such as population, number of households, land area etc.) to proceed. There are various methods for subdividing a study region. The principal rule of choosing a proper dividing method is to ensure data availability for each sub area in the region. This also makes the main factor in deciding the size of sub areas (i.e., if with data available, tracts, blocks and even neighborhoods can be sub study areas). In terms of the ideal size of a sub area, it is assumed that the smaller a sub area is, the more accurate the energy deficit-surplus matching will be. This is because when the sub area is smaller, the more accurate distance between each sub area will be, as the energy deficit-surplus matching currently is based on distance between two sub areas, therefore the smaller sub area division would have more accurate energy deficit-surplus matching. There is an obvious lower limit to defining sub area size: the individual unit of energy demand or supply (i.e., a household in the residential case).

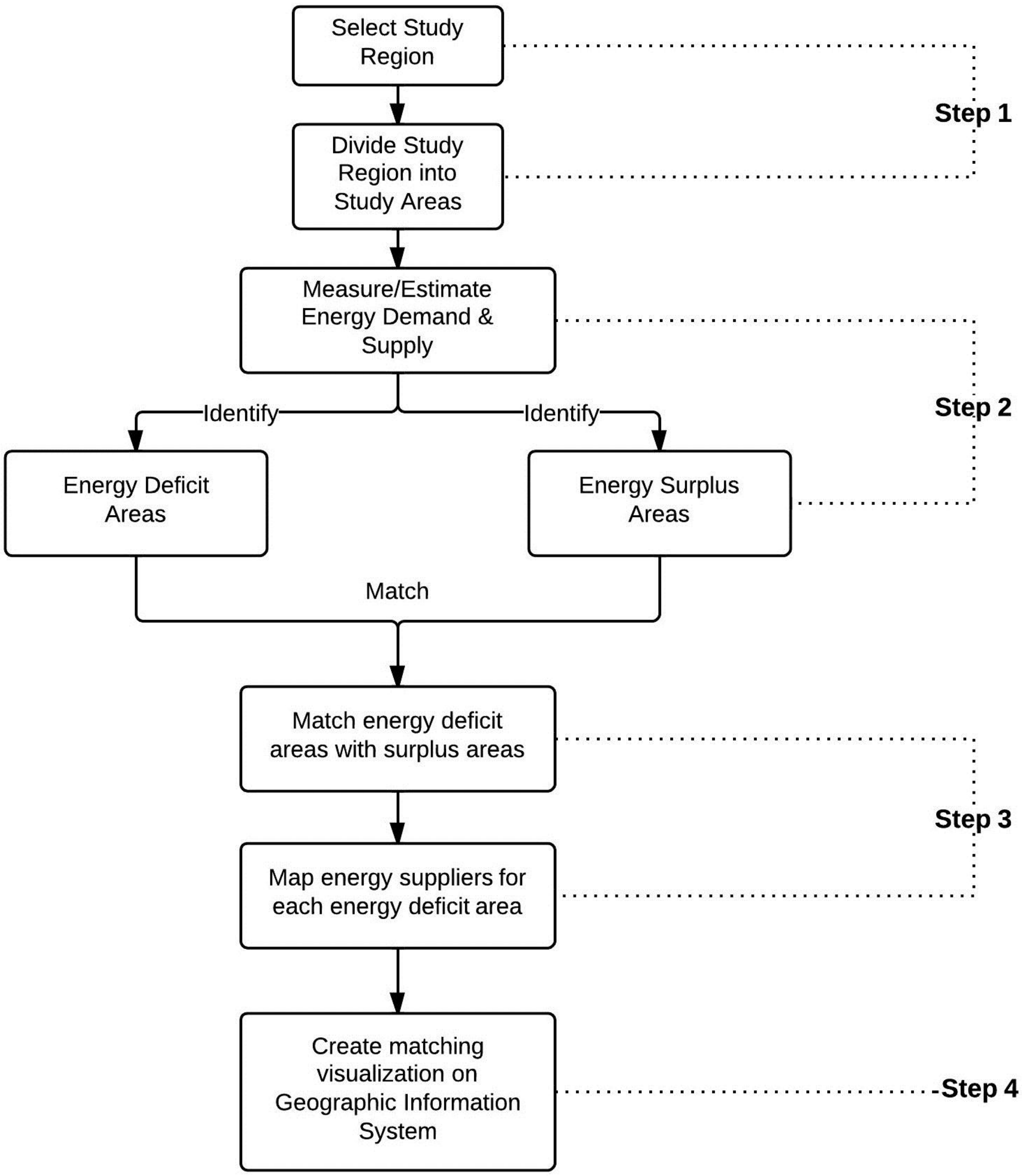

Figure 3.1:Energy Deficit-Surplus Matching Procedure

Step 2 is to identify energy deficit and surplus areas within the study region. This is done by measuring or estimating energy demand and supply for each delineated sub area and then calculating the energy deficit or surplus in each area. An ***energy deficit area*** is an area that does not have enough energy supply to meet its demand (demand > supply), while an ***energy surplus***

area is an area that has more energy supply than its demand (demand < supply). Energy surplus areas are used to construct the energy suppliers for deficit areas in this research. In order to identify energy deficit and surplus areas, energy consumption (demand) per area and energy production (supply) of each area need to be measured or estimated based on information such as energy efficiency, energy consumption per capita or per household, energy production per m^2 or km^2.

Step 3 is to match energy deficit and surplus areas within the study region. Two rules were used here based on the assumptions that: a) the closest (straight-line distance) surplus area is most efficient in cost and accessibility (*Rule A*), and b) the area with the highest deficit should have the first priority to pick energy surplus areas (*Rule B*), because it is assumed to be densely settled, which has more population and economic activities to accommodate.

Rule A. Use the closest surplus area first, and

Rule B. The area with highest deficit has the first priority to pick surplus areas

With respect to *Rule A*, straight-line distance is an important parameter in matching energy deficit and surplus areas. A matrix of pairwise distances between areas in the study region is calculated based on the X-Y coordinates of the population centroid in each area. Population centroids are generated in the geographic information system—ArcGIS. In addition to straight-line distance, other distance criteria such as distance from transmission lines, distance from electricity grid, distance from road network can also be applied.

Rule B is similar to emergency room queuing theory that gives the most injured patient the highest priority in the emergency room. The area with the highest deficit (most likely to be urban core or densely settled area) is assumed to have the most urgent energy demand, and should have highest priority to meet its demand until its deficit is reduced to be equal to or less than the second highest deficit area. At this point, the next greatest deficit area gains the priority. The priority list is dynamic as energy surplus areas are selected and their surplus energy is assigned to deficit areas.

However, there is a concern that it is not decent that the highest deficit area always has first priority to pick energy suppliers, because a big city (such as Toronto in the Ontario case) has a far higher deficit than the second largest deficit area, and it would absorb most of the surrounding energy surplus areas, leaving other deficit areas with much farther energy surplus areas. Or, when there is not enough energy for every deficit area, it is morally wrong to meet highest deficit area first without considering the energy needs of other lower deficit areas. Therefore, an alternate matching method is also proposed to keep the fairness among high and low deficit areas, which is to keep *Rule A*, but change *Rule B* to "all the deficit areas pick energy surplus areas one by one in the order from high to low deficit." The priority list remains fixed as surplus areas are assigned to deficit areas in this alternative.

The two "deficit – surplus" matching methods both have advantages. The first method ensures efficient energy deficit-surplus matching, while the second method takes into account more real-world considerations. Due to time limitations, at this stage I chose the first method over the second to develop the energy deficit-surplus matching tool. Therefore, although the algorithms of both methods are described in this chapter, only the first one is illustrated in the case study. Future work is expected to extend further research on applying both "deficit-surplus" matching methods as well as developing other options, and comparing them. The last step in Figure 3.1 is to create a visualization of matched energy suppliers, which is accomplished by exporting the energy matching results to ArcGIS to generate an energy supplier map for each deficit area.

The method employed in this research mainly relies on Excel Visual Basic for Application (VBA) and Geographic Information System (GIS) for mapping and visualization. ArcGIS is used in Step 1 and 4 (Fig 3.1) in this research, because it allows integration and processing of information from diverse sources. Step 2 and 3 require extensive calculation so it is necessary to have a tool to conduct intensive calculations. Visual Basic for Application (VBA) provides a good environment for this purpose. It enables the building of user-defined functions and automating processes as well as customized user forms. More importantly it works well with ArcGIS, allowing integration of spatial data and energy data.

3.2 A Case Study: Province of Ontario

The study region is the province of Ontario, Canada seen in Figure 3.2. Ontario covers a total land area of 917,741 km^2, and it is Canada's second largest province. Ontario was chosen as the study region for several reasons. First, it is the most populated province in Canada. It had a total population of 13,505,590 as of the 2011 census, comprising 38.7 % of Canada's population (Ontario Ministry of Finance, 2013). It consisted of 574 census subdivisions and 4,887,508 households in 2011 (Statistics Canada, 2012). Second, "Ontario is a study in contrasts" (Government of Ontario, 2013). It has varied landscape that separates the fertile farmland in the south and the grassy lowlands of the north. The southern part is situated south of Algonquin Park, and covers 13% of the province. Northern Ontario constitutes 87% of the land area of

Ontario, yet it only contains about 6% of the population. In contrast, southern Ontario has a larger population and contains the majority of the province's cities, roads and institutions. Third, Ontario is committed to creating a stable and cleaner energy system for the future. Since 2004, Ontario has brought around 3,000 MW of renewable energy sources online including solar, wind and bioenergy (Ontario Ministry of Energy, 2013). And in 2009, the Ontario Green Energy Act (GEA) was introduced to expand renewable energy production, encourage energy conservation and create green jobs (Ontario Ministry of Energy, 2009). Currently there are about 120 generating facilities connected to Ontario's electricity grid—nuclear, hydroelectric, wind, solar PV and bioenergy (Ontario Ministry of Energy, 2013). This thesis focuses on solar PV energy, as solar energy is one of the cleanest, most abundant, and widely distributed renewable energy sources available.

Ontario is a great starting point to illustrate the energy deficit-surplus matching idea and the methods described above. There is a need to understand the potential and capacity of this concept in order to formulate appropriate policy and planning decisions that move Ontario towards energy sustainability and self-sufficiency.

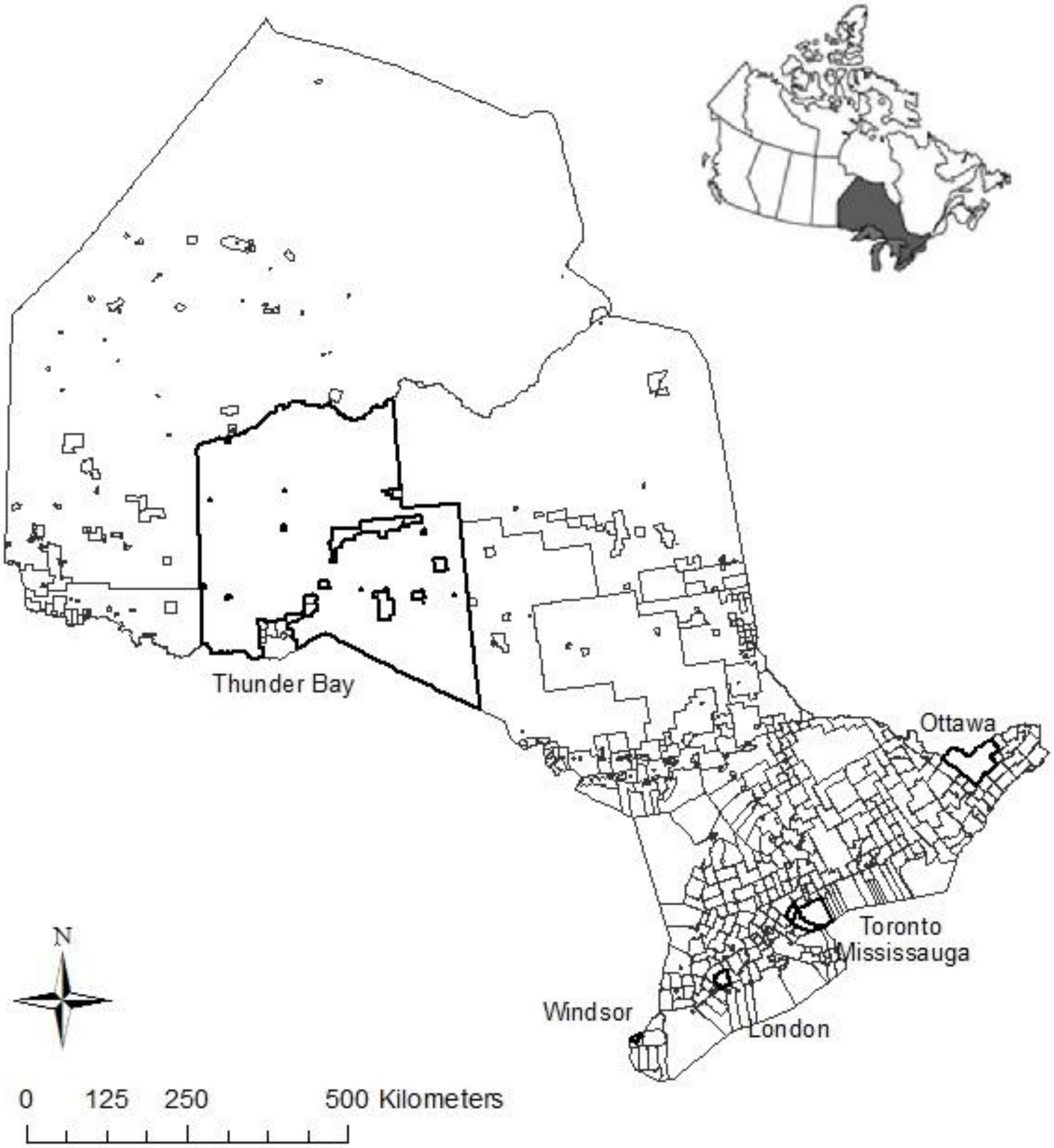

Figure 3.2: Map of Ontario, Canada

3.2.1 Divide Ontario Study Region into Areas

In this Ontario case study, the smallest administrative unit (dissemination area) is the ideal sub area unit. However, as all required information is currently not available for dissemination areas, but these data are available for census subdivisions. Therefore in this research, the administrative units of census subdivisions (CSDs) were chosen as the subdivisions of the Ontario study region because land, population, number of households and other required data were readily available for this spatial unit. The CSD is an administrative division that exists continuously across the region. In Ontario, there are 586 CSDs in 2001, which together cover the entire region and do not overlap. There are seven CSD types in Ontario: City, Town, Township, Village, Indian Reserve, Indian Settlement, and Unorganized (Statistics Canada, 2012). In order to simplify the research design, the seven types of CSDs were reclassified into three categories (Urban, Town and Rural) based on population density similarity, as illustrated in Table 3.1. A map of Ontario's reclassified CSD types is shown in Appendix II. (Note that in this chapter and Chapter 4, Urban stands for Urban CSDs; Town stands for Town CSDs, and Rural stands for Rural CSDs.)

Table 3.1: Reclassification of CSD Types

Label	Original Type	Reclassified as	Population Density (person/km^2)	Description
C	City	Urban	≥≈100 persons/ km^2	Large metropolitans and cities; main energy resource consumer
T	Town	Town	≈50 – ≈100 persons/km^2	Municipalities/subdivisions in between the Urban and Rural levels.
TP	Township			
VL	Village			
R	Indian Reserve	Rural	≤≈50 persons /km^2	Rural areas with relatively less population density than Urban and Town.
S-E	Indian Settlement			
UNO	Unorganized			

3.2.2 Data Description

In order to conduct the energy deficit-surplus matching, Ontario GIS datasets containing the related administrative boundaries and land cover were obtained through Scholars GeoPortal, Ontario Council of University Libraries (Scholars GeoPortal, 2013). The base map is the Ontario municipality boundaries layer. It contains municipal boundaries with CSD (Census Subdivision) name, type, population and dwelling counts, land area and population density values. In order to make the energy deficit-surplus matching more reliable, a land cover and land use analysis was done to exclude unsuitable area for PV development in Ontario. Following datasets were used: the Ontario land cover dataset includes "Provincial Landcover 2000-27 Classes" (Ontario Ministry of Natural Resources, 2002) which provides a classification of 27 broad land cover types north of the southern boundary of the Canadian Shield, within the province of Ontario; "Southern Ontario Canada Land Inventory Land Use" (Ontario Ministry of Natural Resources, 2009) represents the digitized version of the Canada land inventory land use 1:50,000 scale mapping for Southern Ontario; and "Parks & Recreation" regions layer (Ontario Ministry of Natural Resources, 2011) represents over 1,600 national, provincial and territorial parks and over 14,000 recreation areas across Canada.

3.2.3 Estimate Ontario Electricity Supply & Demand

Estimate Ontario Residential Electricity Demand

The Ontario residential instead of commercial, industrial electricity consumption was chosen as case energy demand for this case because there is no readily available measured residential, commercial, or industrial electricity consumption data for each CSD. As residential electricity consumption is closely linked to household in each CSD, it is possible to estimate residential electricity consumption in this research. Therefore, Ontario 2001 residential electricity consumption data were used as energy demand in order to correspond temporally with other data (including population, land area, and households). Electricity intensity and number of households in 2001 were used to estimate residential electricity demand per CSD. Residential electricity demand per CSD is calculated as follows:

$$Electricity\ Intensity = \frac{Total\ Electricity\ Consumption}{Total\ \#\ of\ Households}$$

Eq. 1

$$CSD\ Electricity\ Demand = Electricity\ Intensity\ \times \#\ Households\ in\ each\ CSD$$

Eq. 2

According to the Comprehensive Energy Use database 1990-2010 (obtained from the Office of Energy Efficiency, Natural Resource Canada) the total Ontario residential electricity use in 2001 was 159.8 PJ and total household count was 4,374,800. Therefore, Ontario residential electricity intensity is approximately 10,147 kWh in 2001. The number of households is known in each CSD allowing the electricity demand of each CSD to be calculated. Note that this estimation could be done by other ways with better data. Yet the focus of this thesis is to illustrate the energy deficit-surplus matching approach not to accurately project the electricity consumption patterns, the estimation method used here is considered legitimate.

Estimate Ontario Electricity Supply from Solar PV Only

It is assumed in this research that solar PV is the only supply source for residential electricity demand. The annual solar PV electricity generation of each CSD is determined by PV energy density and available PV area (Ground+Roof) calculated as follows:

$$CSD\ PV\ generation = PV\ energy\ density\ \times CSD\ Available\ PV\ area$$

Eq. 3

$$CSD\ Available\ PV\ area\ = PV\ land\ occupation\ fraction\ \times CSD\ land\ area$$

Eq. 4

PV energy density is the amount of PV electricity generated per unit of land surface area (m^2) annually in kWh. It is determined by a series of factors such as incident solar radiation, PV technology type, PV array power density, orientation, tilt, shading and AC conversion efficiency. *Available PV area* in this research refers to ground and rooftop area available for deployment of solar PV systems, and is determined by the PV land occupation fraction, which is a ratio of the total area (ground+ roof) devoted to PV development to the total land area in the study region. It shows that in order to meet a certain demand of electricity, how much of the total land area of the study region is required to deploy PV generation (ground + roof). Ideally there would be separate considerations of feasible roof area in urban centers and feasible land area in rural areas. However, at this stage of the development, this thesis did not consider land area and roof area separately for PV deployment. Further work could be extended to explore how much ground and roof area separately can be utilized in Urban, Town and Rural CSDs for PV development. And it is already known that roof area shares a correlation with population (Izquierdo et al., 2008; Kumar, 2004; Lehmann & Peter, 2003; Taubenbock et al., 2008). A study done by Wiginton et al., suggested that 70 m^2/capita is a very reasonable estimation of roof area per person in the Canadian context (Wiginton, Nguyen, & Pearce, 2010).

In this research, PV energy density is assumed to be 75kWh/m^2/year, which is based on estimates in Denholm & Margolis (2008). In their research, an "ecological footprint" (which typically is calculated for an individual or region to estimate the energy and associated footprint with all consumed goods and services) approach is applied to estimate the land area required to supply all end-use electricity from solar PV in the United States. Taking all above mentioned factors and all PV system types into account, average PV density is estimated on a state-by-state basis. It is also found that the PV area (ground + roof) required to meet the national electricity demand with solar PV deployed is about 0.6% of the total land area of United States. In Michigan, PV density was estimated to be 75kWh/m^2/year and required PV land occupation fraction is around 3% to meet its electricity demand (Denholm & Margolis, 2008).

A comparison of annual solar radiation of Ontario and Michigan was done through RETScreen (see Appendix III) which indicates that Ontario and Michigan have similar annual solar radiation; and also it shows that there are only minor differences while in annual average solar radiation among climate locations across Ontario (Kenora in northern Ontario has annual solar radiation as 3.72 kWh/m^2/day and Windsor in southern Ontario has 4.03 kWh/m^2/day seen in Appendix III). Since Ontario is situated in a similar geographical context to Michigan, it is reasonable to assume that it has a similar PV density and PV land occupation fraction as Michigan as a starting point.

In terms of total land area, Ontario's varied landscape offers an abundance of natural resources. Around 66% of Ontario's land is classified as forested land. Ontario has vast system of parks and protected areas as well as many lakes, rivers and streams that flow through the entire province. Even though solar PV technology is theoretically applicable anywhere on Earth, it is not realistic or desirable to deploy solar energy in forests, wetlands and other environmentally sensitive areas (Jacobson, 2009). Therefore, a land cover analysis of Ontario was done to exclude areas that are not suitable for deployment of solar PV. Two different layers: provincial landcover 2000 (Ontario Ministry of Natural Resources, 2002) and Southern Ontario Canada Land Inventory Land Use map (Ontario Ministry of Natural Resources, 2009) were used and mosaicked into one land cover/use map of Ontario. As these two land-cover and land-use maps were not consistent in classification schemes and layer types, some conversion and reclassification was done to accommodate the merge. A detailed reclassification description is shown in Appendix IV. Six land classes were summarized for the mosaicked land cover map: watershed, urban, rural, forest depletion (where the land is not suitable for forest use any more, which can be converted for other uses such as solar and wind farms), dense forest, and agriculture. In this research, watershed and dense forest as well as provincial and national parks are considered not suitable for PV energy; hence these three classes were excluded from the total land area available. In addition, the unknown land in this Ontario case only occupies a small insignificant area and it is neither water bodies nor dense forest areas (unsuitable for PV), therefore it is grouped with urban land class assuming it could be suitable for PV development, but less available than in rural and other land classes. A map of this land exclusion analysis for the study region is shown in Appendix V.

PV land occupation fraction usually varies in Urban, Town and Rural category CSDs. However, as the Denholm & Margolis research did not provide separate estimated PV land occupation fractions for either urban or rural areas, and there is no further specific research has addressed this issue under the North American context, therefore 3% is chosen for this research as a legitimate maximum PV land occupation fraction for total available land area in Ontario after the land exclusions of unsuitable PV areas. And this 3% applies to all Urban, Town and Rural CSDs in Ontario for this research. It is expected future work would separate the considerations of PV land occupation fractions in urban and rural areas.

3.2.4 **Energy Deficit-Surplus Matching Tool and Its Development**

Energy deficit-surplus matching tool is a tool written in Visual Basic for Applications (VBA) that conducts a series of calculations with imported spatial data, in order to match electricity surplus CSDs for electricity deficit CSDs within the study region. The tool is currently written to work with only Canadian census data though it can be readily modified to work with other data types.

Tool Parameters & Functionality:

Based on the estimation of Ontario residential electricity supply and demand described in Section 3.2.3, there are a total of seven parameters in the tool, six of which require user input in order to proceed with calculation and matching energy deficit-surplus CSDs (unshaded and pink shaded in Table 3.2) and one parameter is automatically calculated by the tool (green shaded in Table 3.2). A summary explanation of these parameters is shown in Table 3.2.

PV System Energy Density is the annual average solar PV system electricity generation per square meter, which is used to calculate potential PV electricity supply of each CSD. *Electricity Intensity* is the annual average household residential electricity consumption, which is used to calculate electricity demand of each CSD based on the number of households in each CSD. *Max PV Land Occupation Fraction* is a parameter to show the maximum area that PV (ground +roof) is allowed to occupy as a fraction of the total (Urban+Town+Rural) land area. These three parameters are developed based on Eq. 1-4 in Section 3.2.3.

Table 3.2: Parameters Summary of Energy Deficit-Surplus Matching Tool

(Calculated parameter is green shaded; optional parameters are pink shaded)

Parameter	Explanation	Data Type	Default Value
PV System Energy Density	Annual average solar PV system energy generation per m^2: $\text{PV Energy Density} = \frac{\text{Annual PV Generation}}{\text{Land Area}}$	kWh/m^2	$75kWh/m^2$/ year
Electricity Intensity	Annual average household residential electricity consumption: $\text{Electricity Intensity} = \frac{\text{Total Electricity Consumtion}}{\text{\# of households}}$	kWh/household	10147 kWh/ household /year
Max PV Land Occupation Fraction $\boldsymbol{\alpha}$	The maximum fraction of PV land occupation: $\alpha = \frac{\text{Available PV area (Ground + Roof)}}{\text{Total land area}}$	%	3%
Category Supply Fraction	Supply fraction of each Urban, Town, Rural category CSDs: $U = \frac{Supply_{urban}}{Demand\_Total}$ $T = \frac{Supply_{town}}{Demand\_Total}$ $R = \frac{Supply_{rural}}{Demand\_Total}$ $Supply_{Total}$ = Supply_urban + Supply_town + Supply_rural $\frac{Supply\_total}{Demand\_total} = \frac{Supply_{urban} + Supply_{town} + Supply_{rural}}{Demand\_total} = \frac{U + T + R}{1}$ (U,T,R should be all $\leq \beta$)	%	No Default Values
Max Category Only Supply Fraction $\boldsymbol{\beta}$ (Calculated)	$\beta = \frac{Supply_{cat}}{Demand_{Total}} = \frac{PV\ Density \times Category\ Land \times \alpha}{Electricity\ Intensity \times Total\ Households}$	N/A	
Basic Electricity Demand Ratio (Optional)	Fraction of total electricity demand required to satisfy basic human needs	≤100%	100%
Distance Cap (Optional)	Ceiling distance restriction in energy matching calculation. E.g. can be set as 200km, to restrict all energy suppliers must fall within this distance.	km	200km

Category Supply Fraction is a parameter for users to customize different supply fraction combinations for Urban, Town and Rural categories, in order to create different supply-demand relations for scenario analysis. *Category supply fraction* is the fraction of category (Urban/Town/Rural) energy supply to the total energy demand. i.e., Urban supply fraction is 30%, then it means that Urban CSDs supply 30% of the total demand; Town supply fraction is 45%, then Town CSDs supply 45% of the total demand; and Rural supply fraction is 25%, then it means Rural CSDs supply 25% of the total demand. Together, Urban, Town and Rural CSDs supply a 100% (30%+45%+25%) of the total energy demand. Therefore, different Urban, Town and Rural supply fraction combinations – total value of Urban, Town Rural supply fractions – could create desired supply-demand relations. *Max Category Only Supply Fraction* is designed as a calculated parameter to serve as an upper bound on the user-entered *Category Supply Fraction* parameter (*Category Supply Fraction*≤ *Max Category Only Supply Fraction*). It is determined by the *Max PV Land Occupation Fraction* indicating the maximum available energy supply of each Urban, Town, Rural CSD category for the total electricity demand in study region. For instance, max Urban only supply fraction means that maximum fraction of Urban CSDs total energy alone can supply to the total energy demand in the study region. More details about *Max Category Only Supply Fraction* and *Category Supply Fraction* parameters are discussed in Section 3.2.5 for case study and exploratory scenarios.

In addition, as mentioned in the description of the two matching methods in Section 3.1, a planning conflict can occur when two big energy deficit CSDs are located very close to each other. The CSD with higher energy deficit would absorb most of the nearby energy suppliers and leave the other deficit CSD with farther suppliers, which is not realistic or decent. Although the first matching method - the one that does not consider fairness and moral issues - was used in this research, two optional functions are developed in the energy deficit-surplus matching tool in an attempt to make the tool more flexible for real world energy planning. *Basic Electricity Demand Ratio* is an optional parameter, which requires a pre-set basic electricity demand ratio (a fraction of each CSD's electricity demand to support human basic needs, which varies under different situations) for all deficit CSDs. It looks for energy surplus CSDs under the restriction of meeting basic electricity demand for every deficit CSD first; After all deficit CSDs' basic electricity demands are satisfied, then it recalculates and searches for energy surplus CSDs to meet the remaining deficits in each CSD. This parameter is more likely to be applied in an electricity poverty situation and this thesis does not study the estimation of this ratio but focuses on illustrating the application and function of this parameter. *Distance Cap* is another optional parameter that was created for a similar purpose as *Basic Electricity Demand Ratio.* It is a user-defined distance limit to restrict energy deficit-surplus matching calculation within the defined distance (e.g. 200 km). Both *Basic Electricity Demand Ratio* and *Distance Cap* are designed to tackle the same issue but in different ways. *Basic Electricity Demand Ratio* provides the option to set a clear quantity cap (how much basic electricity demand for each CSD should be met first), while *Distance Cap* provides the option to set a specific distance cap of how far a deficit CSD can go to get energy surplus CSDs. Both parameters to some degree ensure fairness and avoid the monopolization of energy surplus areas by big deficit CSDs like Toronto.

Tool Algorithm

Since energy deficit-surplus matching requires extensive calculations, the energy deficit-surplus matching tool is developed to conduct a series of calculations to match energy surplus CSDs for energy deficit CSDs within the study region. The algorithm of the energy deficit-surplus matching tool is shown in Figure 3.3 and is described here. It starts with getting applicable user input for each parameter. It then calculates the distance between each CSD in the study region based on the X-Y coordinates of population centroids in each CSD. This is done one time and all the calculated distance is stored as a distance matrix. The population centroid is used (instead of geometric centroid) to generate distance matrix because residential electricity consumption is closely connected to where population is located. A distance matrix by FID—Feature ID (Feature ID is a unique object ID created in ArcGIS to identify records in attribute tables in a geodatabase) of each CSD is created, where FID is extracted from Ontario Municipal Boundary shape file attributes.

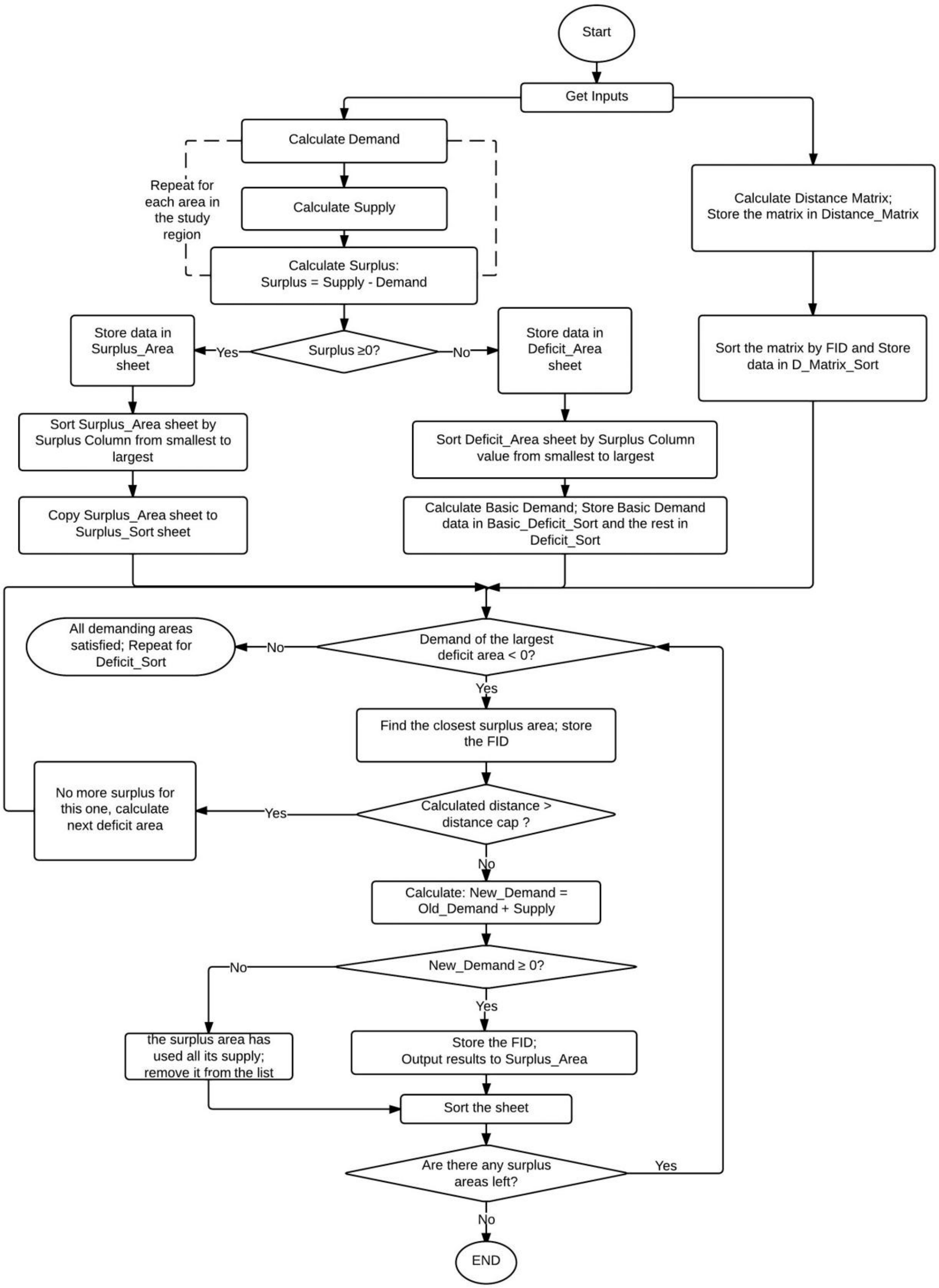

Figure 3.3: Algorithm of the Energy Deficit-Surplus Matching Tool

Electricity supply and demand is then calculated in the tool based on the imported data and user inputs. Each CSD's electricity surplus is then calculated by taking supply minus demand. If the surplus≥ 0, it is stored in the worksheet Surplus_Area; if the surplus is< 0, it is stored in the Deficit_Area worksheet. Both sheets are then sorted by values from smallest to greatest. The *Basic Electricity Demand* of each deficit CSD is then calculated and stored in the Basic_Demand_Sort sheet based on the *Basic Electricity Demand Ratio* and deficit CSDs with the rest of electricity demand (after excluding basic electricity demand) are stored in Deficit_Sort. Then starting from the CSD with the largest deficit (i.e., the most negative value of supply minus demand), the tool first checks the deficit value, referring to "Demand of the largest deficit area< 0" box in Figure 3.3 above. If it is≥ 0, then all deficit areas are satisfied and the electricity deficit-surplus matching ends. If the deficit is< 0, then the tool will find the closest electricity surplus CSD in the Surplus_Area sheet and check to see if the deficit is satisfied with the remaining surplus in that CSD. If no, it means all the surplus in that CSD is used up and the tool will remove it from the Surplus_Area list and resort the Deficit_Sort list from the highest deficit to the lowest deficit. On the other hand, if the deficit is satisfied with the remaining surplus in that surplus CSD, it means some of the surplus may still be remaining. The tool will then store the remaining energy surplus and keep that surplus CSD on the list. This matching continues one by one from Deficit_Sort and Surplus_Area sheets until no surplus CSDs are left in the sheet, or all deficit CSDs are satisfied. If the optional parameter Distance Cap is chosen, the matching will have one more step: if the closest surplus CSD is farther than preset Distance Cap (e.g. 200km), then it stops matching for the current deficit CSD and starts matching for the next highest deficit CSD. If the closest surplus CSD is not father than the preset distance cap, then matching continues for that deficit CSD until it is satisfied within that distance cap or there are no more surplus CSDs within the distance cap.

As mentioned in Section 3.1 there is another matching method that keeps *Rule A*, but has *Rule B* as “all the deficit areas pick energy surplus areas one by one in the order from high to low deficit.” The priority list remains fixed in this case. The alternative algorithm for this matching method is shown in Appendix VI. The algorithm is substantially the same as the above one but with a slight difference in the matching procedure. This alternate algorithm matches the study CSDs in Surplus_Area and Deficit_Area sheets one by one without sorting the Deficit_Area sheet after matching for one deficit CSD. This prevents energy “hogs” from absorbing all the surplus CSDs before any other deficit CSDs has a chance to pick, resulting in energy suppliers that are biased towards the needs of large urban areas.

Work Flow

Although the energy matching tool helps with the extensive calculations and matching energy deficit and surplus CSDs, it requires necessary user input. A schematic diagram of the workflow for this process is shown in Figure 3.4 below.

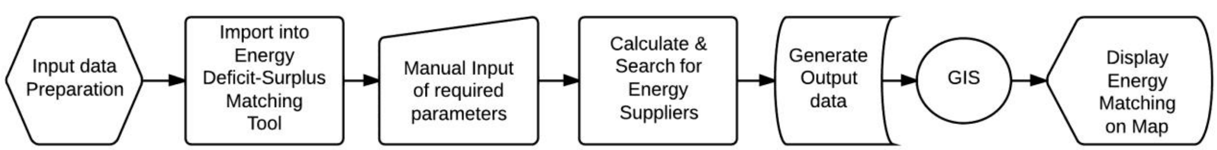

Figure 3.4: Work Flow of Energy Deficit-Surplus Matching

Data preparation is important. Input data include: a base map of the study region with delineated areas (CSDs), an Excel file that contains Feature ID, Name, Land type, Population and Dwellings and Land area of each CSD, as well as geographic X-Y coordinates of each CSD that are generated in ArcGIS based on population centroids. With all required data ready, they are then imported into the energy deficit-surplus matching tool. Next enter the applicable parameter values and run the tool. After the run is finished, enter the FID of any selected deficit CSD of interest (because the tool only outputs results for one CSD at a time), the tool generates two Comma Separated Values (CSV) files that are output to the same folder as energy deficit-surplus matching tool: one containing all the electricity deficit and surplus CSDs with FID; and the other contains surplus CSDs with FID, CSD name, electricity surplus (kWh), which deficit areas (by FID) are being supplied surplus electricity from that CSD, and how much (% of deficit) each surplus CSD supplied to each deficit CSD. Also, total electricity demand, supply and surplus of the study region will be displayed on the Results_sheet in the tool. The last step is to import these output CSV files into ArcGIS to generate energy matching maps. A detailed energy deficit-surplus matching tool user guide is provided in Appendix VII.

Verification of the tool

The energy deficit-surplus matching tool calculation was verified by manual calculations to examine the tool-calculated results for the roles of energy deficit areas and energy surplus areas under different situations. Toronto, Thunder Bay, Prince Edward, and Hilton were selected as test CSDs based on the energy matching results (Toronto-high deficit, Thunder Bay-low deficit, Prince Edward-high surplus, Hilton-low surplus). The electricity demand and potential solar PV electricity supply of these four CSDs were manually calculated based on imported data and input parameter values. Toronto and Thunder Bay were then verified as electricity deficit CSDs, while Prince Edward and Hilton were verified as electricity surplus CSDs. Electricity deficit and surplus CSD matching was also verified by manual calculations. Toronto electricity suppliers (surplus CSDs that supply Toronto’s electricity deficit) were selected one at a time by distance (closest first) between Toronto and each surplus CSD. The same matching calculations were also conducted for Thunder Bay. The deficit CSDs that Prince Edward and Hilton supply were similarly identified through manual calculations. The energy deficit-surplus matching tool results were then compared to the manual calculations and found to be the same. Approximately 10 other CSDs were randomly spot-checked for further verification, and in all cases the energy deficit-surplus matching tool results were the same as those from manual calculations, verifying that the tool is an accurate implementation of the energy deficit-surplus matching algorithm.

3.2.5 **Ontario Residential Electricity Self-Sufficiency Case Study:**

As stated in Chapter 1, this research explores two research questions: "Is the energy deficit-surplus matching approach useful in determining whether a region can reach energy self-sufficiency on an annual basis through only renewable energy supply?" And "How does the energy matching approach distribute areas in order to balance energy deficit and surplus within the study region?" The goal of this case study is to demonstrate that it is feasible for Ontario to be self-sufficient by getting all its 2001 residential electricity from only solar PV generation within the provincial boundary under current technology and land allowances; and relying on the developed energy deficit-surplus matching approach, electricity suppliers of each electricity deficit CSD within Ontario can be identified. It is hoped that this case study could provide answers for two research questions.

Energy self-sufficiency mathematically means energy supply equals energy demand within a given area over a given period of time. In this case, Ontario 2001 residential electricity demand equals Ontario 2001 solar PV generation (Demand: Supply = 1:1) is desired. Therefore, the following exercises are designed to explore the possibility of achieving this Demand: Supply = 1:1 relation, using the energy deficit-surplus matching tool. Figure 3.5 below shows the procedure of conducting the case study exercises. It begins with getting the input data imported to the tool, and then entering appropriate values for each tool parameter. Next, assign supply fractions to each previously reclassified Urban, Town, Rural category, based on the desired supply-demand relationship. The last step is to run the energy deficit-surplus matching tool and generate results.

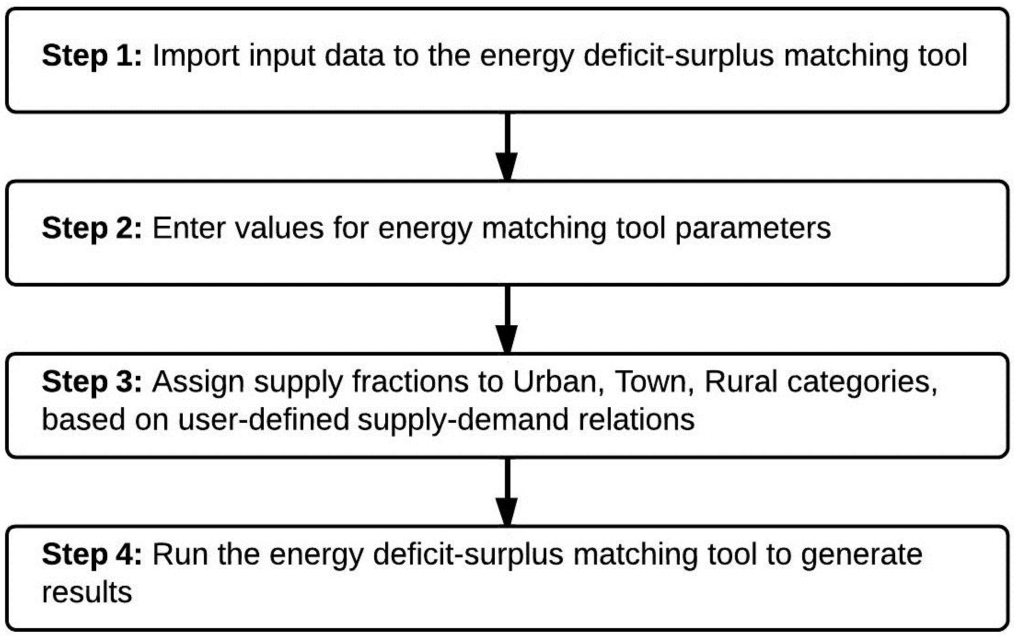

Figure 3.5: Case Study Exercise Procedure

With input data for the case study ready, it is imported into the energy deficit-surplus matching tool. Step 2 in Figure 3.5 is to enter values for energy matching parameters. As this case explores the feasibility of achieving Ontario residential electricity self-sufficiency from only solar PV generation under current technology and land allowance, *PV System Energy Density* and *Electricity Intensity* parameters are set to default values, and *Max PV Land Occupation Fraction* is set to 3%, as detailed in Section 3.2.3. Also note that because *Basic Electricity Demand Ratio* and *Distance Cap* are two optional parameters, at the first phase of this case study they are not considered (left unselected in the tool), but are addressed and explored in Section 3.2.6. See Table 3.3 for a summary table of preset values for the five above-mentioned parameters.

Table 3.3: Preset Parameter Values for Self-Sufficiency (Demand: Supply=1:1) Case

Parameter	Value
PV System Energy Density	75kWh/m2/year
Electricity Intensity	10147 kWh/ household /year
Max PV Land Occupation Fraction	3%
Basic Electricity Demand Ratio (Optional)	Not selected
Distance Cap (Optional)	Not Selected

Referring to Step 3 in Figure 3.5, the category supply fractions of the Urban, Town, and Rural CSD categories need to be assigned in order to run the tool. Figure 3.6 shows an example of reclassified Urban, Town and Rural CSDs in Ontario. As explained in Section 3.2.4, *Category Supply Fraction* is a parameter that determines the fractions that each Urban, Town and Rural category CSDs supplies to meet the total Ontario residential electricity demand. Recall that this case study considers energy demand to be 2001 Ontario residential electricity consumption and 2001 solar PV generation as the only energy supply. In order to achieve an Ontario residential electricity Demand: Supply = 1:1 relation, the total of category (Urban/Town/Rural) supply fractions needs to be 100% (see explanation in Section 3.2.4 "Tool Parameters & Functionality"). Also, recall that as explained in Section 3.2.4, *Category Supply Fraction* should be less than or equal to *Max Category Only Supply Fraction*.

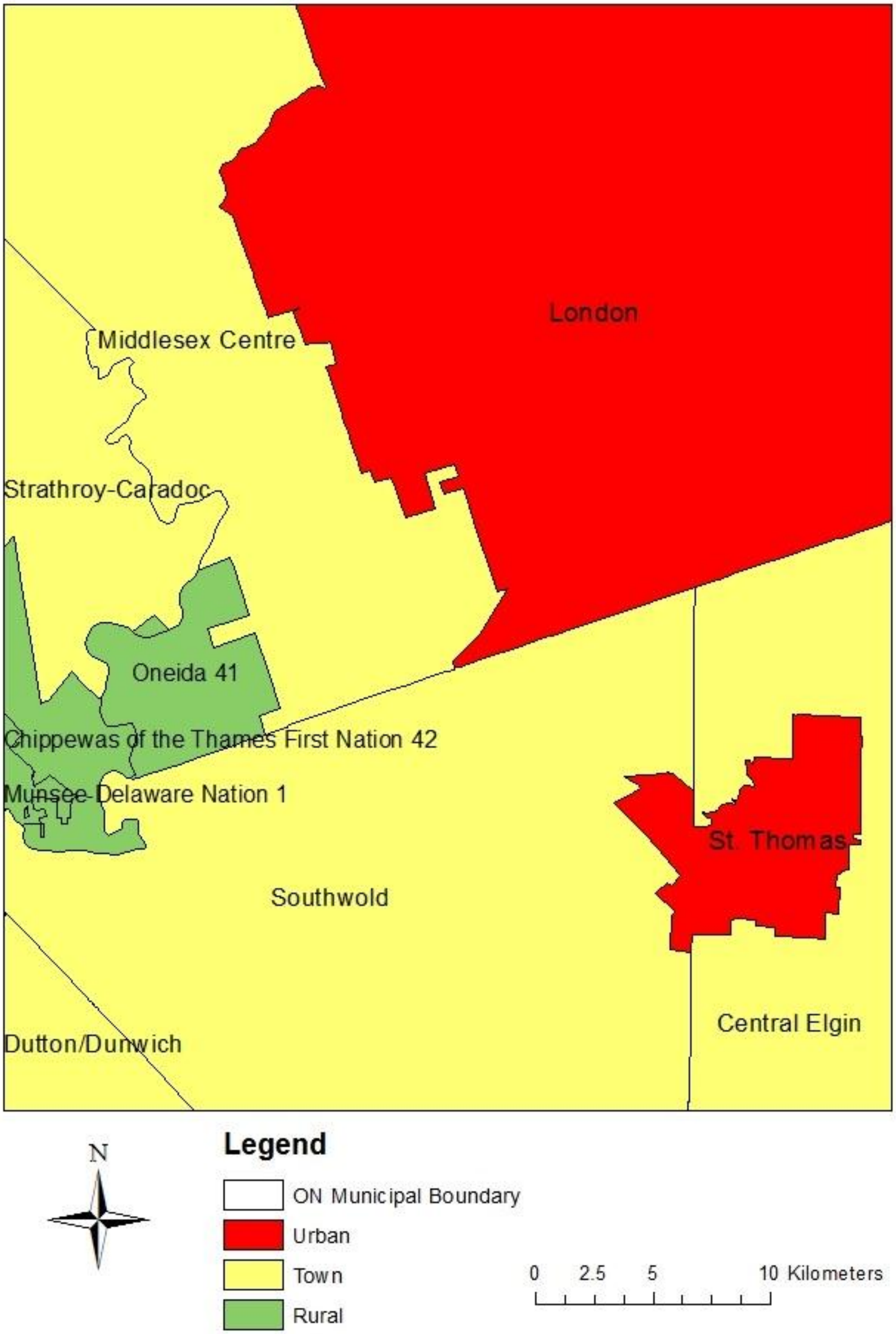

Figure 3.6: An Example of Reclassified Ontario CSDs

The *Max Category Only Supply Fraction* is calculated in the tool as described in Section 3.2.4 "Tool Parameters & Functionality" using the total Ontario residential electricity use in 2001 (159.8 PJ $\cong 44,389$ GWh), the preset parameter values in Table 3.3, and energy deficit-surplus matching tool import data (an Excel file that contains Feature ID, Name, Land type, Population and Dwellings and Land area of each CSD):

$$Max\ Category\ Only\ Supply\ Fraction = \frac{Max\ Supply_{cat}}{Demand_{Total}}$$

$$= \frac{PV\ Density \times Total\ Category\ Land\ Area \times Max\ PV\ land\ occupation\ fraction}{Demand_{Total}}$$

For example, based on energy matching tool import data, total Urban land area is 14351.18 km^2. Then with total electricity demand of 44,389 GWh and other preset values from Table 3.3, max Urban only supply fraction is calculated as $\frac{75kWh/m2 \times 14351.18\ km2 \times 3\%}{44{,}389\ GWh}$ ≈96% which means Urban CSDs alone can supply up to 96% of the total electricity demand. A similar calculation gets Max Town supply fraction to be 316% (which means Town CSDs alone can supply 3.16 times the total electricity demand), and Max Rural supply fraction is 843% (which means Rural CSDs alone can supply 8.43 times the total electricity demand). *Max Category Only Supply Fraction* is a calculated parameter, and it serves as a filling limit for *Category Supply Fraction*. Hence in this case study, the Urban supply fraction parameter can be assigned with a value between 0 and 96%, the Town supply fraction parameter can vary from 0 to 316%, and the Rural supply fraction parameter can vary from 0 to 843%.

As mentioned in Chapter 1, one objective of this thesis is to understand how energy deficit-surplus matching result responds to supply fraction combinations of areas of differing population density (Urban, Town, Rural) under varying supply-demand relations. Therefore, a sensitivity analysis was done to investigate how the (Urban/Town/Rural) category supply fraction combinations affect energy deficit-surplus matching results. Low, Medium, and High supply fraction (of total energy demand) for each category is designed to explore how the energy deficit-surplus matching result responds to different combinations of category supply fraction. In this thesis, the Low supply fraction is defined to represent very little or nearly zero supply ($Low \geq\approx 0$); Medium supply fraction is defined to represent moderate supply, but less than or equal to half of the total demand ($Low < Medium \leq 1/2\, Total$); and High supply fraction is defined to represent over half of total demand ($1/2\, Total < High \leq Total$). To conduct this sensitivity analysis under the self-sufficiency case (Demand: Supply=1:1), the total of (Urban/Town/Rural) category supply fractions need to be 100%; also under the restriction that category supply fractions must not exceed the *Max Category Only Supply Fractions*. 1% was set as a Low supply fraction, 30% was set as a Medium supply fraction, and 69% was set as a High supply fraction. Under this self-sufficiency case, this selection of Low-Medium-High values has restricted the possible combinations of category supply fractions down to six (See Table 3.4). Note that these values are set by the author for this sensitivity analysis to see how energy matching results change over wide range of change in these category supply fractions. Other groups of values were also applied and showed no obvious change in the energy deficit-surplus matching. Further research could test how sensitive energy matching results are to different sets of these parameter values.

Table 3.4: Category Supply Fractions for Self-Sufficiency (Demand: Supply=1:1) Case

Category Supply Fraction Combinations	Supply Fractions Category Breakdown		
	Urban	Town	Rural
Combination 1	1%	30%	69%
Combination 2	1%	69%	30%
Combination 3	30%	1%	69%
Combination 4	30%	69%	1%
Combination 5	69%	1%	30%
Combination 6	69%	30%	1%

Table 3.4 displays the six combinations of Urban, Town and Rural supply fractions under the self-sufficiency case. The first column shows the total six combinations; and the second column shows the breakdown of total 100% supply fraction shares to Urban, Town, and Rural categories respectively for each combination. The energy deficit-surplus matching tool was run based on parameter values from Table 3.3 and 3.4. The results generated are discussed in Chapter 4.

3.2.6 Exploratory Scenarios

In addition to the self-sufficiency case, two exploratory scenarios were explored to demonstrate the flexibility of the method and to investigate energy deficit-surplus matching results under different demand-supply relations (Step 3 in Figure 3.5), when residential electricity demand (*Electricity Intensity*) and solar PV technology (*PV system Density*) stay the same as in the self-sufficiency case (see Table 3.3). Scenario 1 exemplifies an electricity poverty situation when supply is only half of the demand (Demand: Supply = 1: 0.5). Scenario 2 demonstrates an electricity richness situation that when supply is 10 times the demand (Demand: Supply = 1: 10). PV land allowance (*Max PV land occupation fraction*) was adjusted to formulate Scenario 2. It is acknowledged that these scenarios do not represent the full variety of real-world situations, but were included to study the influence of category supply fractions under different supply-demand relations on energy matching results.

Scenario A: Demand: Supply = 1: 0.5

Making the assumption that 2001 total Ontario solar PV supply is half of 2001 total residential electricity demand; this scenario investigates the situation that PV production in Urban, Town and Rural category CSDs is limited. Urban, Town, and Rural supply much less to the total electricity demand in this scenario than in the self-sufficiency case. Under this condition, in order to make Demand: Supply = 1: 0.5, the total value of Urban, Town and Rural supply fractions should be 50%. Referring to the sensitivity value setting logic for low-medium-high supply fraction in the self-sufficiency case, in Scenario A, 1% [out of 50%] is set as Low supply fraction, 15% [out of 50%] is set as Medium supply fraction and 34% [out of 50%] is set as High supply fraction Under Scenario A, this selection of Low-Medium-High values has restricted the possible combinations of category supply fractions down to six (See Table 3.5). Table 3.5 and Table 3.6 in the following section share a similar format as Table 3.4. Again, note that these values are set by the author for this sensitivity analysis to see how energy matching results change over wide range of change in these category supply fractions. Other groups of values were also applied and showed no obvious change in the energy deficit-surplus matching results. Further research could test how sensitive energy matching results are to different sets of these parameter values.

Table 3.5: Category Supply Fractions for Demand: Supply=1:0.5 Scenario

Category Supply Fraction Combinations	Supply Fractions Category Breakdown		
	Urban	Town	Rural
Combination 1	1%	15%	34%
Combination 2	1%	34%	15%
Combination 3	15%	1%	34%
Combination 4	15%	34%	15%
Combination 5	34%	1%	15%
Combination 6	34%	15%	1%

Scenario B: Demand: Supply = 1: 10

This scenario assumes that 2001 total solar PV energy supply exceeds 2001 total residential electricity demand by a great deal and is 10 times the total electricity demand. This scenario investigates the situation when available PV area in Urban, Town and Rural CSDs is excessive, Urban, Town, and Rural areas supply much more than in the self-sufficiency case. In order to formulate this scenario, *Max PV Land Occupation Fraction* was adjusted to be 30%, large enough to ensure the calculated *Max Category Supply Fraction* parameter is great enough for assigning category (Urban/Town/Rural) supply fractions in order to make the total of them to be 1000% for Scenario B.

In Scenario B, the total of category supply fractions needs to be 1000%. Again, referring to the sensitivity value setting logic for low-medium-high supply fraction in the self-sufficiency case, in Scenario B, 1% [out of 1000%] is set as a Low supply fraction, 300% [out of 1000%] is set as a Medium supply fraction and 699% [out of 1000%] is set as a High supply fraction. Under Scenario B, this selection of Low-Medium-High values has restricted the possible combinations of category supply fractions down to six (See Table 3.6). Once again, these values are set by the author for this sensitivity analysis to see how energy matching results change over wide range of change in these category supply fractions. Other groups of values were also applied and showed no obvious change in the energy matching results. Further research could test how sensitive energy deficit-surplus matching results are to different sets of these parameter values.

Table 3.6: Category Supply Fractions for Demand: Supply=1:10 Scenario

Category Supply Fraction Combinations	Supply Fractions Category Breakdown		
	Urban	Town	Rural
Combination 1	1%	300%	699%
Combination 2	1%	699%	300%
Combination 3	300%	1%	699%
Combination 4	300%	699%	1%
Combination 5	699%	1%	300%
Combination 6	699%	300%	1%

Furthermore, illustrations of applying two optional parameters: *Distance Cap* and *Basic Electricity Demand Ratio* to mitigate energy deficit-surplus matching conflicts between big energy deficit CSDs were done. Two optional parameters were applied respectively to the self-sufficiency (Demand: Supply= 1:1) case. The category supply fraction sensitivity combinations stay the same as in Table 3.4.

Distance Cap

As described in Section 3.2.4, *Distance Cap* is an optional parameter that restricts the energy matching within a user defined distance limit, in order to avoid big deficit CSDs absorbing all nearby energy surplus areas. Table 3.7 below shows the preset parameter values for illustrating this Distance Cap parameter. 200km is chosen as a reasonable value for this illustration. Other distance-limit assumptions may also be applied.

Table 3.7: Preset Parameter Values for Distance Cap Illustration

Parameter	Value
PV System Energy Density	75kWh/m2/year
Electricity Intensity	10147 kWh/ household /year
Max PV Land Occupation Fraction	3%
Basic Electricity Demand Ratio (Optional)	Not selected
Distance Cap (Optional)	200 km

Basic Electricity Demand Ratio

Basic Electricity Demand Ratio is another optional parameter created to indicate the fraction of electricity demand that needs to be met first for all deficit areas, before some bigger deficit areas absorb all nearby energy surplus areas. Table 3.9 shows the preset parameter values for this illustration. The *Basic Electricity Demand Ratio* was set to be 57%, which is based on the U.S. Energy Information Administration 2011 electricity consumption by end-use breakdown, as seen in Appendix VIII. Judging from the electricity consumption breakdown, the author considers space cooling, lighting, water heating, refrigeration, space heating, and cooking, as the basic residential electricity needs (this may vary in different context, this thesis does not discuss the estimation of this ratio). In total, these end uses account for 57% of the total electricity consumption.

Table 3.8: Preset Parameter Values for Basic Electricity Demand Ratio Illustration

Parameter	Value
PV System Energy Density	75kWh/m2/year
Electricity Intensity	10147 kWh/ household /year
Max PV Land Occupation Fraction	3%
Basic Electricity Demand Ratio (Optional)	57%
Distance Cap (Optional)	Not Selected

3.3 Summary

This chapter details the energy deficit-surplus matching methods, and applies the proposed approach to the Ontario context as a case study to achieve residential electricity self-sufficiency from only solar PV generation on an annual basis. A VBA-based energy deficit-surplus matching tool was developed to assist in applying the energy matching approach. A self-sufficiency case was investigated under category supply fraction Low-Medium-High sensitivity combinations. In addition, two more exploratory scenarios of different demand-supply relations were also investigated as part of the sensitivity analysis for understanding the relationship between category (Urban/Town/Rural) supply fraction and energy deficit-surplus matching results. Two optional parameters were also run with valid assumptions to illustrate their functions. Results of the self-sufficiency case study, exploratory scenarios, and optional parameter illustrations are displayed and analyzed in the following chapter.

Chapter 4 Results & Discussion

This chapter discusses results of the Ontario residential electricity self-sufficiency case and exploratory scenarios outlined in Chapter 3. Section 4.1 illustrates the results of the self-sufficiency case in an attempt to answer the first research question: "**Is the energy deficit-surplus matching approach useful in determining whether a region can reach energy self-sufficiency on an annual basis through only renewable energy supply?**" Section 4.2 displays energy deficit-surplus matching results for three major urban CSDs in trying to provide answers to the second research question: "**How does the energy matching approach distribute areas in order to balance energy deficit and surplus within the study region?**" Sections 4.3 and 4.4 present results and discussion for exploratory scenarios and optional parameter function as part of the sensitivity analysis of category supply fraction combinations and energy deficit-surplus matching results. Section 4.5 summarizes the chapter.

4.1 Ontario Residential Electricity Self-Sufficiency from PV

As stated in Ontario's Long-Term Energy Plan, "Ontario families and businesses need a reliable, efficient and clean electricity system from a variety of resources" (Ontario Ministry of Energy, 2012), it is clear that Ontario is targeting a cleaner energy future. Therefore, achieving residential electricity self-sufficiency from solar PV energy will have profound significance for Ontario.

The results generated by the energy deficit-surplus matching tool for the case study indicate that it is feasible for Ontario to achieve residential electricity self-sufficiency from only solar PV energy on an annual basis. Table 4.1 is an extended version of Table 3.4 with additional columns on the right showing the output actual PV land occupation fraction in Urban, Town, and Rural category CSDs under the self-sufficiency case (total provincial residential electricity demand equals total solar PV energy supply potential). The output actual PV land occupation in each category was generated by the energy deficit-surplus matching tool based on the user-entered parameter values shown in Table 3.3 and Table 3.4. It can be seen in Table 4.1 that every PV land occupation fraction in three (Urban, Town, Rural) categories does not exceed the maximum 3% of PV land occupation fraction. This could be interpreted to mean that it is possible to supply all 2001 residential electricity demand of the whole province using less than 3% of Ontario total land area to deploy solar PV technology (ground + roof). Therefore, the answer to the first research question, "Is the energy deficit-surplus matching approach useful in determining whether a region can reach energy self-sufficiency on an annual basis through only renewable energy supply?" is positive.

Table 4.1: Output PV Land Occupation of Urban, Town, Rural Category

Category Supply Fraction Combinations	Supply Fractions Category Breakdown			Output PV Land Occupation of Each Category		
	Urban	Town	Rural	Urban	Town	Rural
Combination 1	1%	30%	69%	0.031%	0.284%	0.246%
Combination 2	1%	69%	30%	0.031%	0.654%	0.107%
Combination 3	30%	1%	69%	0.936%	0.009%	0.246%
Combination 4	30%	69%	1%	0.936%	0.654%	0.004%
Combination 5	69%	1%	30%	2.153%	0.009%	0.107%
Combination 6	69%	30%	1%	2.153%	0.284%	0.004%

Relying on the energy deficit-surplus matching approach, Ontario 2001 residential electricity self-sufficiency can be achieved by balancing energy deficit and surplus within the provincial boundary. Based on the results generated from energy deficit-surplus matching tool, Figure 4.1 shows a map of the electricity deficit and surplus CSDs in Ontario under the self-sufficiency case, where red indicates electricity deficit CSDs; and green indicates electricity surplus CSDs.

Figure 4.1 was generated under Combination 6 in Table 4.1 where Urban supplying 69% (High) of total demand, Town supplying 30% (Medium) and Rural supplying 1% (Low). This combination is chosen for the illustration here because it indicated that although large electricity deficit (Urban) CSDs such as Toronto, Mississauga and London supplying high fraction of total electricity demand, they are still in electricity deficit, which implies their electricity demand is beyond their solar PV supply potential. This is because Urban area usually have higher population density and consumes more electricity per unit area while they have less space available for solar PV generation; therefore Urban areas usually tend to have more electricity deficits than Town and Rural areas. Also, some large CSDs in northern Ontario, such as Thunder Bay, North Part Sudbury, and Rainy River are electricity deficit CSDs despite their small population. This is mainly because those CSDs are classified as Rural, and in this combination Rural supplies 1%(Low) of the total demand, so there is only 0.004% of Rural CSD land area devoted to solar PV. It could happen in reality that a large part of Rural CSDs is unsuitable for PV due to other restrictions (e.g., legal, aboriginal issues), or there is low population in these areas that result in small urban areas, which have very little open land for solar PV development.

In conclusion, it is technically feasible for Ontario to achieve residential electricity self-sufficiency with electricity deficit CSDs and surplus CSDs balancing supply-demand within the region. The proposed energy deficit-surplus matching approach is useful in determining whether a region can reach energy self-sufficiency on an annual basis through only renewable energy supply.

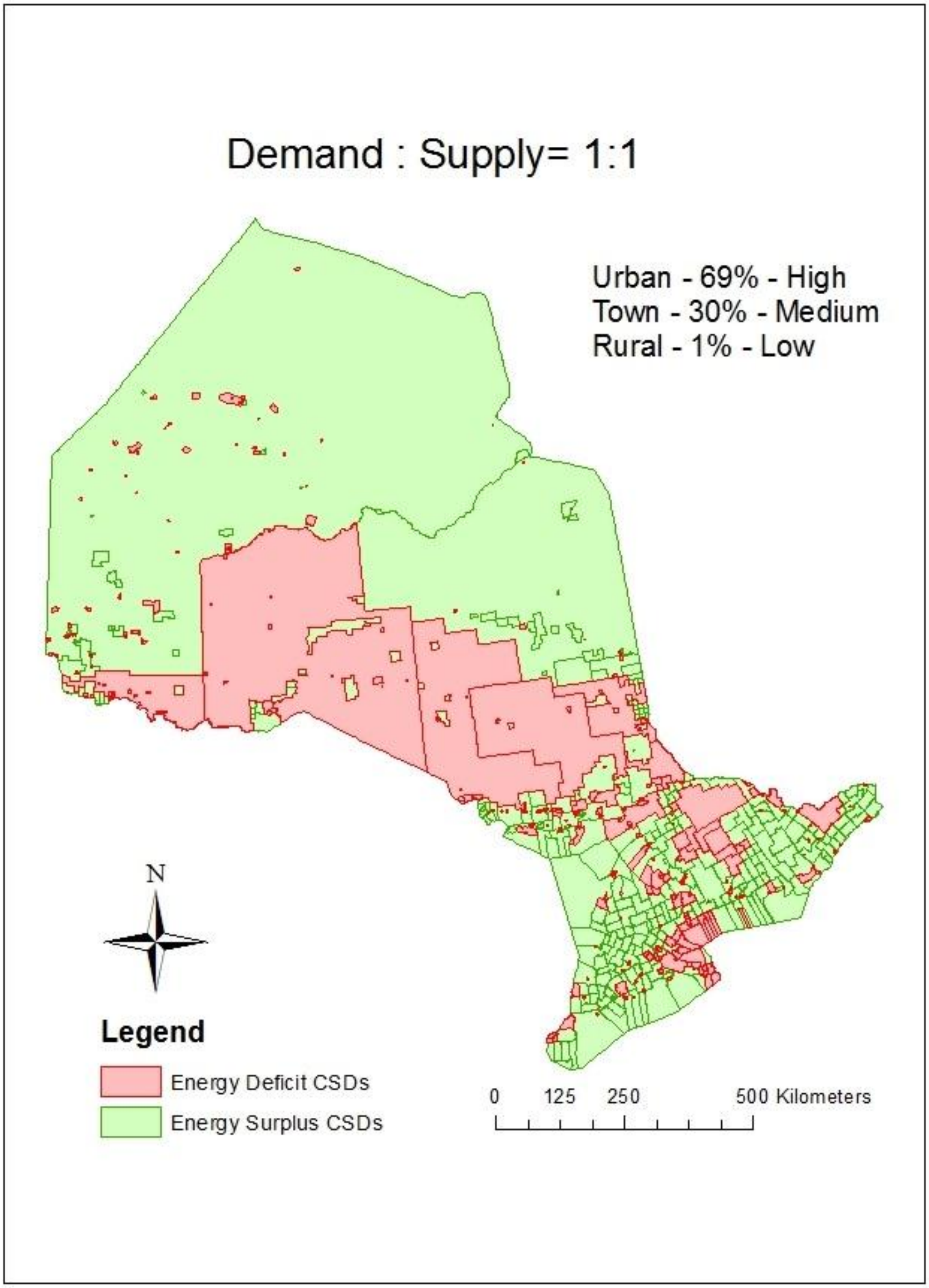

Figure 4.1: Electricity Deficit and Surplus CSDs in Ontario

4.2 PV Electricity Suppliers for Major Urban CSDs

Section 4.1 demonstrated that it is possible for Ontario to achieve residential electricity self-sufficiency from solar PV generation by balancing electricity supply-demand between electricity deficit and surplus CSDs within the region. This section discusses the electricity suppliers (surplus areas) possibilities for electricity deficit CSDs (in red) in Figure 4.1 to meet their unmet electricity demand with the study region.

Table 4.2 lists the top 20 electricity deficit CSDs in Ontario (based on 2001 annual electricity consumption). It can be seen that Toronto occupies the top position with -9,428,917,376 kWh of electricity deficits, followed by Mississauga with a -1,823,353,947 kWh electricity deficit; Ottawa is ranked number three with a -1,539,616,238 kWh deficit. The big residential electricity deficits result from the large population densities and small area available for PV in those three metropolitan areas.

Table 4.2: Top 20 Electricity Deficit CSDs in Ontario

Rank	CSD Name	Deficit (kWh)
1	Toronto	-9,428,917,376
2	Mississauga	-1,823,353,947
3	Ottawa	-1,539,616,238
4	Hamilton	-1,263,882,133
5	London	-1,214,838,084
6	Brampton	-828,549,258
7	Windsor	-822,837,628
8	Kitchener	-675,953,114
9	Markham	-534,297,449
10	St. Catharines	-501,651,984
11	Burlington	-490,431,723
12	Oakville	-453,802,186
13	Oshawa	-447,531,223
14	Vaughan	-385,735,795
15	Richmond Hill	-382,151,886
16	Guelph	-378,243,113
17	Barrie	-351,186,137
18	Thunder Bay	-350,577,756
19	Cambridge	-335,804,823
20	Waterloo	-321,692,886

Source: Generated based on energy deficit-surplus matching tool calculations

Figure 4.2 shows composite energy deficit-surplus matching results for six major electricity deficit CSDs: London, Windsor, Ottawa, Brampton, Mississauga and Toronto under the supply fraction Combination 4 in Table 4.1 where Urban supplying 30% (Medium) of total demand, and Town supplying 69% (High) and Rural supplying 1% (Low) of total demand. This combination is selected out of six combinations in Table 4.1 based on the assumption that Urban areas are unlikely to support large amounts of solar PV and supply a high fraction of total demand. And Town areas, which are generally closer to Urban areas but with less population density and electricity consumption, could potentially provide a high supply fraction of total demand.

In Figure 4.2, color blocks represent large electricity deficit CSDs, and corresponding color highlight lines represent electricity suppliers for each deficit CSD. It can be seen that under the Urban supplies Medium, Town supplies High and Rural supplies Low combination, every deficit CSD starts to obtain energy surplus areas from its nearby surroundings, except for Brampton and Mississauga which get farther energy surplus areas due to Toronto has absorbed all nearby suppliers. Overall, this resulting energy deficit-surplus matching result reflects a good picture of the anticipated decentralized sustainable energy system.

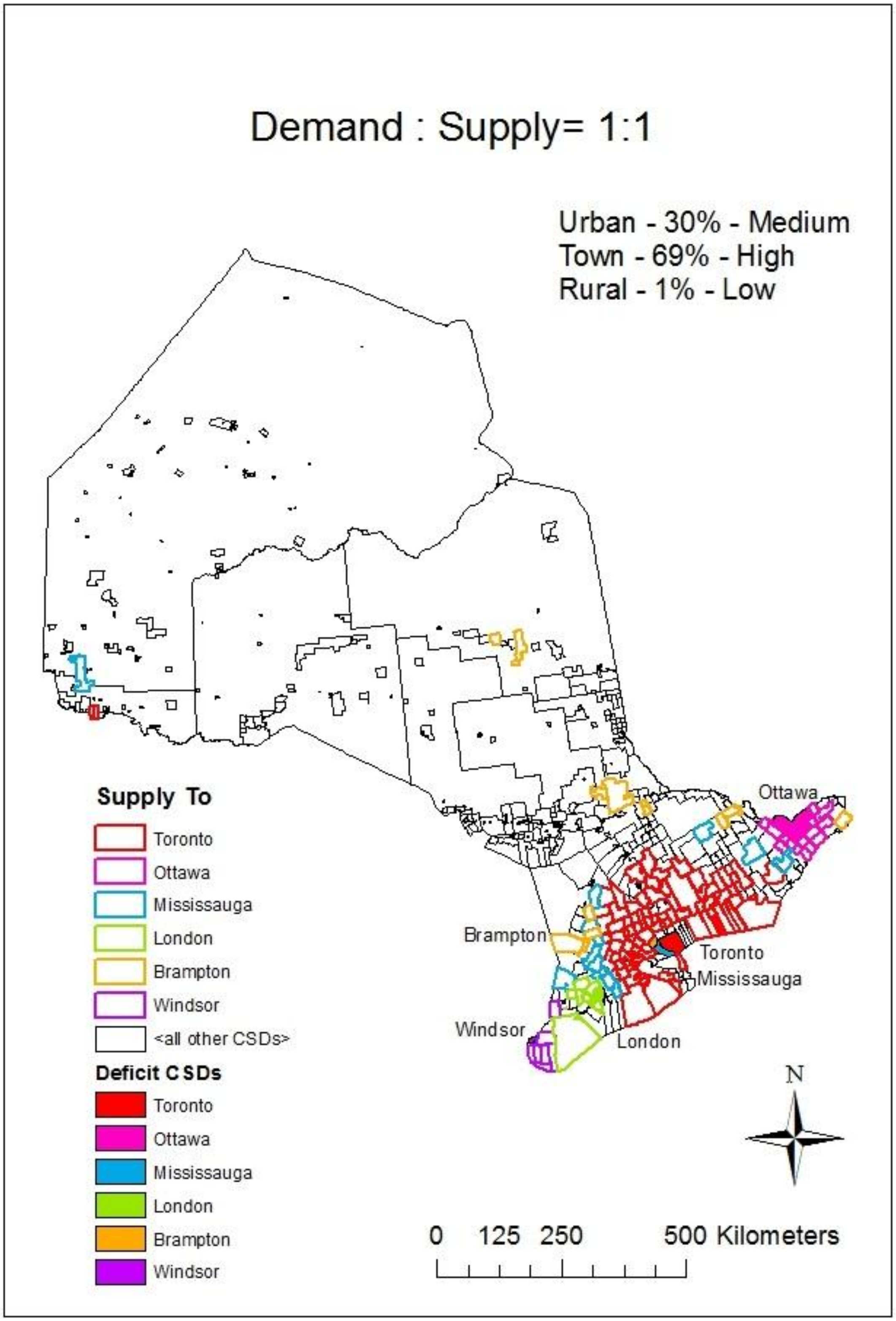

Figure 4.2: Electricity Suppliers for Major Urban CSDs in Ontario

4.2.1 **Toronto-Ottawa-Mississauga**

Under the Ontario residential electricity self-sufficiency case, three large urban CSDs Toronto, Ottawa, and Mississauga were selected to illustrate the question "How does the energy matching approach distribute areas in order to balance energy deficit and surplus within the study region?" Figure 4.3, 4.4 and 4.5 are small multiple illustrations of electricity suppliers for each selected CSD. A small multiple is a series or grid of small similar graphics or charts, allowing difference among objects to be easily compared (Tufte, 2001). In Figure 4.3 name of CSD (Toronto) is shown at the left end, with Demand-Supply relation indicated below. Above each small electricity suppliers distribution graph, category supply fraction combination is shown in abbreviations: e.g. U stands for Urban, T stands for Town, and R stands for Rural; and supply fractions are abbreviated to be 0.1 for 1%, 0.69 for 69% and 0.3 for 30%. Same format and abbreviations apply to all small multiple figures in this chapter.

Figure 4.3 shows electricity suppliers distributions for Toronto under different category (Urban/Town/Rural) supply fraction sensitivity combinations. In Figure 4.3, the red block represents Toronto, and blue lines highlight Toronto's electricity suppliers. Toronto has the most electricity deficits because of its large population and electricity consumption. It can be seen from Figure 4.3 that different supply fractions of Urban, Town and Rural would greatly affect electricity suppliers distributions for Toronto. The first illustration in Figure 4.3 shows when Urban supplies 1% (Low) of total demand, Town supplies 30% (Medium) and Rural supplies 69% (High) of the total demand, Toronto needs to go far north to meet its electricity demand; while in the fourth illustration, when Town supplies 69% (High) of total demand, Toronto only needs nearby towns as electricity suppliers to meet its demand, and the last illustration in Figure

4.3 shows that when Urban supplies 69% (High) of total demand, and Town supplies 30% (Medium) and Rural supplies 1% (Low) of total demand, Toronto obtains less some nearby towns as electricity suppliers than in fourth illustration, and also gets some farther electricity suppliers. The reason is as the supply fraction of Town drops from 69% (High) to 30% (Medium); some previous electricity surplus CSDs become electricity deficit CSDs.

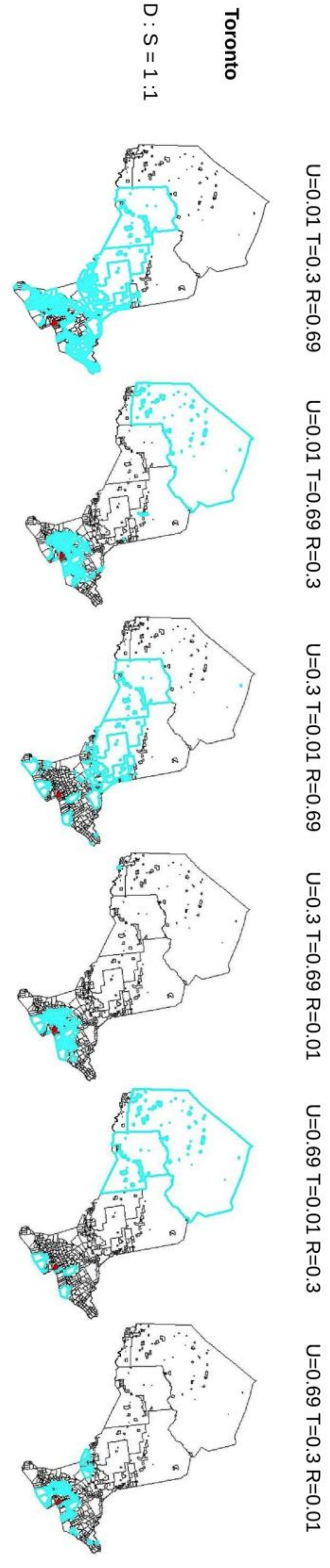

Figure 4.3: Electricity Suppliers for Toronto

Compared to Toronto, Ottawa has a smaller population density, and therefore has less electricity demand. Figure 4.4 shows electricity suppliers distributions of Ottawa under low, medium, high combination of supply fraction of Urban, Town, and Rural. A similar trend is detected as in Figure 4.3 that as Urban and Town supply fractions increase, the deficit CSD in question can meet its electricity demand with fewer electricity suppliers. The last illustration in Figure 4.4 has shown that Ottawa could be self-sufficient (needs no electricity suppliers) when Urban supplies high, and Town supplies medium and Rural supplies low fractions of the total demand.

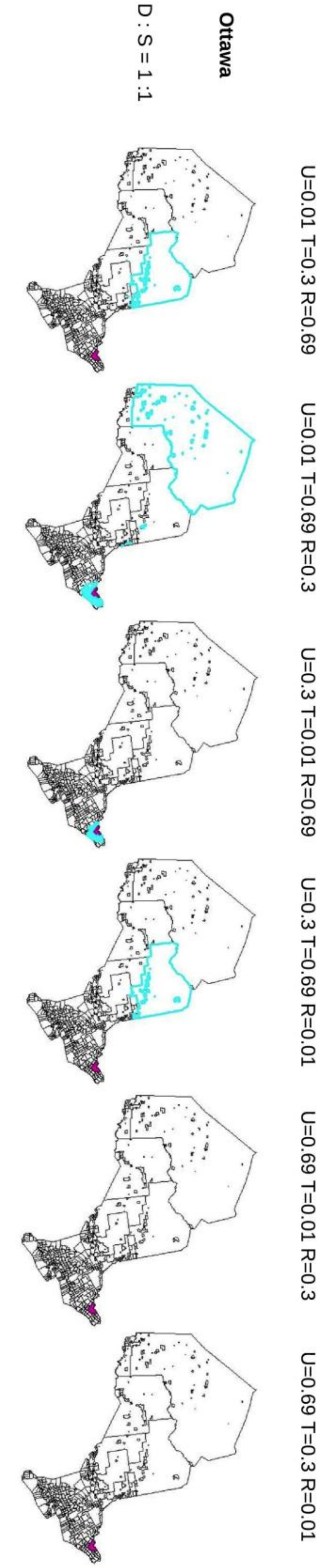

Figure 4.4: : Electricity Suppliers for Ottawa

Mississauga is the second largest electricity deficit CSD following Toronto. Figure 4.5 shows the electricity suppliers distributions of Mississauga under low, medium, high supply fraction of Urban, Town, and Rural. The same trend is detected as in the Toronto and Ottawa cases that as Urban and Town supply fraction increases, a smaller electricity supplier distribution results. One particular point in the Mississauga case is that Toronto (as the largest deficit CSD) has taken most of the nearby surplus CSDs as electricity suppliers, which left Mississauga, the second largest deficit CSD, fewer nearby suppliers. Mississauga has to go farther for suppliers. This issue can be seen in all illustrations in Figure 4.5: Mississauga cannot have electricity suppliers from neighbouring CSDs, but has to go far up to northern Ontario for electricity suppliers, as all surrounding suppliers are taken by Toronto. Possible solutions for this issue are detailed in Section 4.4 this chapter.

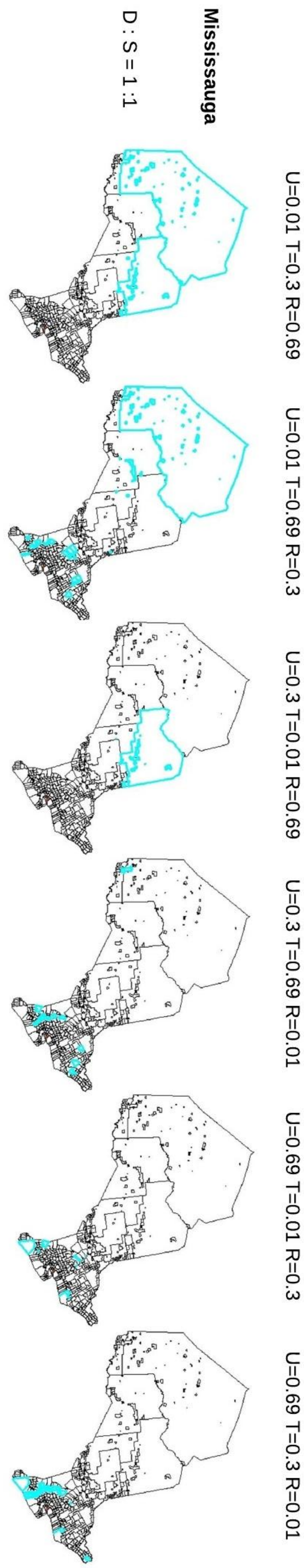

Figure 4.5: Electricity Suppliers for Mississauga

4.3 Exploratory Scenarios

As introduced in Section 3.2.6, two exploratory scenarios were conducted to explore how the category supply fraction combinations under different total supply-demand relations influence energy deficit-surplus matching results in the study region. This section will analyze the results for these two scenarios in order to understand how energy matching responds to category supply fraction sensitivity combinations under two extreme supply-demand relations.

4.3.1 Scenario A: Demand: Supply = 1: 0.5

This scenario assumes that Ontario's solar PV generation can only supply half of Ontario's total electricity demand. This scenario might happen in reality when less area in Urban, Town and Rural is devoted to PV development. Other reasons could also be technical (low PV density) and social (high household electricity consumption). As in this research, PV density and household electricity consumption are fixed; only the amount of available PV area was investigated. Table 4.3 listed the sensitivity supply fractions and the resulted fractions of available total area devoted to solar PV development in all three categories.

Table 4.3: Scenario A Supply Fraction Combinations & Output PV Land Occupation

Category Supply Fraction Combinations	Supply Fractions Category Breakdown			Output PV Land Occupation of Each Category		
	Urban	Town	Rural	Urban	Town	Rural
Combination 1	1%	15%	34%	0.031%	0.142%	0.121%
Combination 2	1%	34%	15%	0.031%	0.322%	0.053%
Combination 3	15%	1%	34%	0.468%	0.009%	0.121%
Combination 4	15%	34%	15%	0.468%	0.322%	0.004%
Combination 5	34%	1%	15%	1.061%	0.009%	0.053%
Combination 6	34%	15%	1%	1.061%	0.142%	0.004%

4.3.2 Scenario B: Demand: Supply = 1: 10

This scenario assumes that solar PV energy supplies 10 times of the residential electricity demand for the province. This scenario would happen under the circumstances that when PV density and electricity consumption are fixed, a significant amount of (roof + ground) area is devoted to develop solar PV. Table 4.4 lists the sensitivity supply fraction of each CSD category and the resulting output PV land occupation fractions. It is noted that under this scenario, the maximum category available PV area ratio was set to be 30% in order to make the total supply 10 times of the total demand. Table 4.4 listed the sensitivity supply fractions and the resulted fractions of available total area devoted to solar PV development in all three categories.

Table 4.4: Scenario B Supply Fraction Combinations & Output PV Land Occupation

Category Supply Fraction Combinations	Supply Fractions Category Breakdown			Output PV Land Occupation of Each Category		
	Urban	Town	Rural	Urban	Town	Rural
Combination 1	1%	300%	699%	0.031%	2.845%	2.488%
Combination 2	1%	699%	300%	0.031%	6.628%	1.068%
Combination 3	300%	1%	699%	9.359%	0.009%	2.488%
Combination 4	300%	699%	1%	9.359%	6.628%	0.004%
Combination 5	699%	1%	300%	29.075%	0.006%	1.068%
Combination 6	699%	300%	1%	29.075%	1.897%	0.004%

4.3.3 Scenario Summary

This section summarizes findings from above two mentioned scenarios for three previously selected urban electricity deficit CSDs: Toronto, Ottawa and Mississauga. Figure 4.6 shows the electricity suppliers distributions for Toronto under different combination of (Urban, Town, Rural) supply fractions in Scenario A and B. The first row in Figure 4.6 contains generated electricity supplier distributions for Scenario A; and the second row shows generated electricity supplier distributions for Scenario B. The same layout is used for Figure 4.7 and 4.8. It is assumed that the fewer electricity suppliers a deficit CSD needs the better; and also the closer the electricity suppliers, the better. These two rules are the principles of understanding the electricity supplier distribution illustrations in following small multiples.

As shown in Figure 4.6, 4.7 and 4.8, electricity supplier distribution changes when supply-demand relation changes. As the total supply-demand relation becomes from 1: 0.5 to 1: 10, most deficit CSDs can be self-sufficient and need no electricity suppliers. And in Figure 4.6 Demand: Supply= 1: 10 relation, when Urban supplies Medium – 300% of total demand, which takes approximately 9.359% of total Urban area, according to Table 4.4. Toronto, the largest deficit CSD, only needs a few surrounding electricity suppliers to meet its demand; and when Urban supplies High (usually not realistic in real world), Toronto can be self-sufficient, needing no suppliers at all. Therefore, max PV land occupation is crucial in determining the maximum PV supply potential in each category CSDs. When the max PV land occupation was adjusted to be 30% (rarely happen in real world), most of the Urban CSDs could be energy self-sufficient. Also Urban supply fraction is the key in these changes. For one big deficit CSD (usually be urban areas), a higher Urban supply fraction results in fewer electricity suppliers needed.

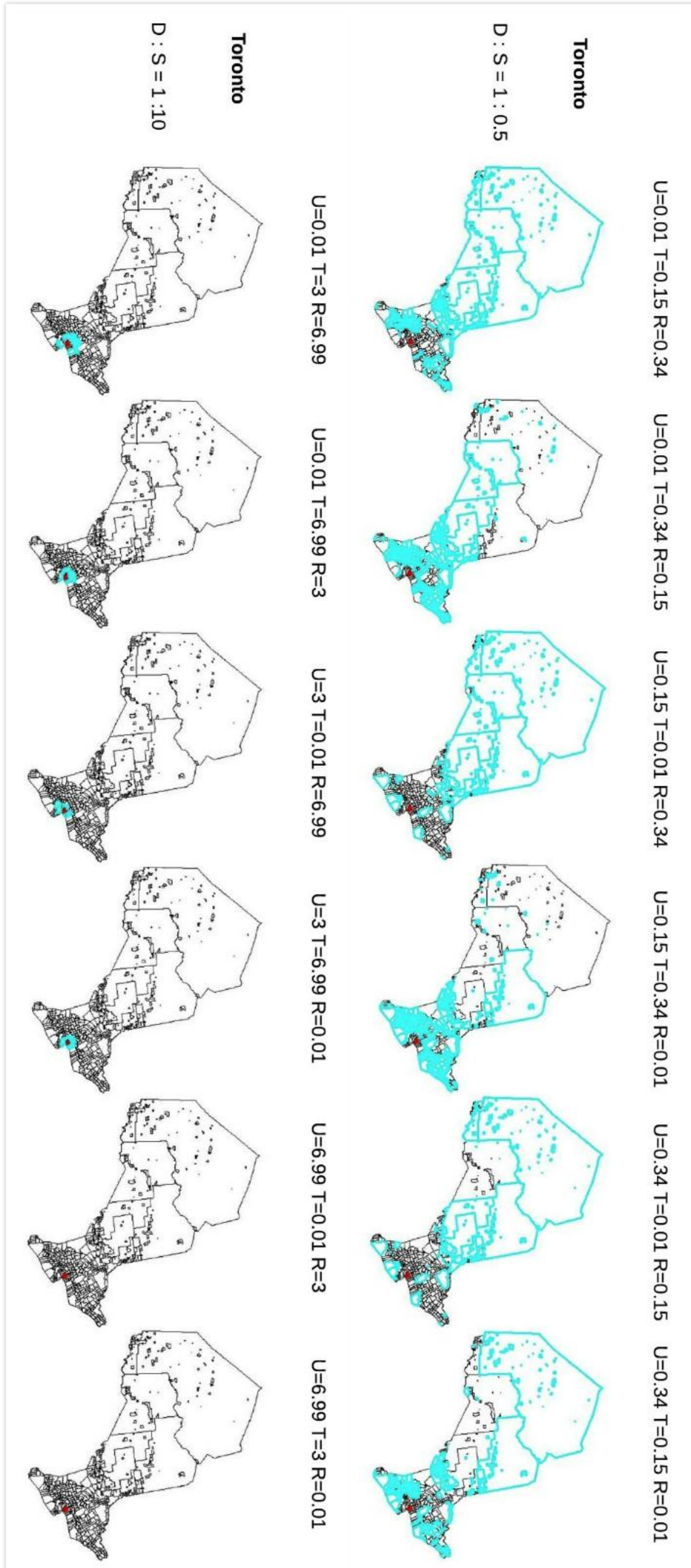

Figure 4.6: Toronto Electricity Suppliers Small Multiples

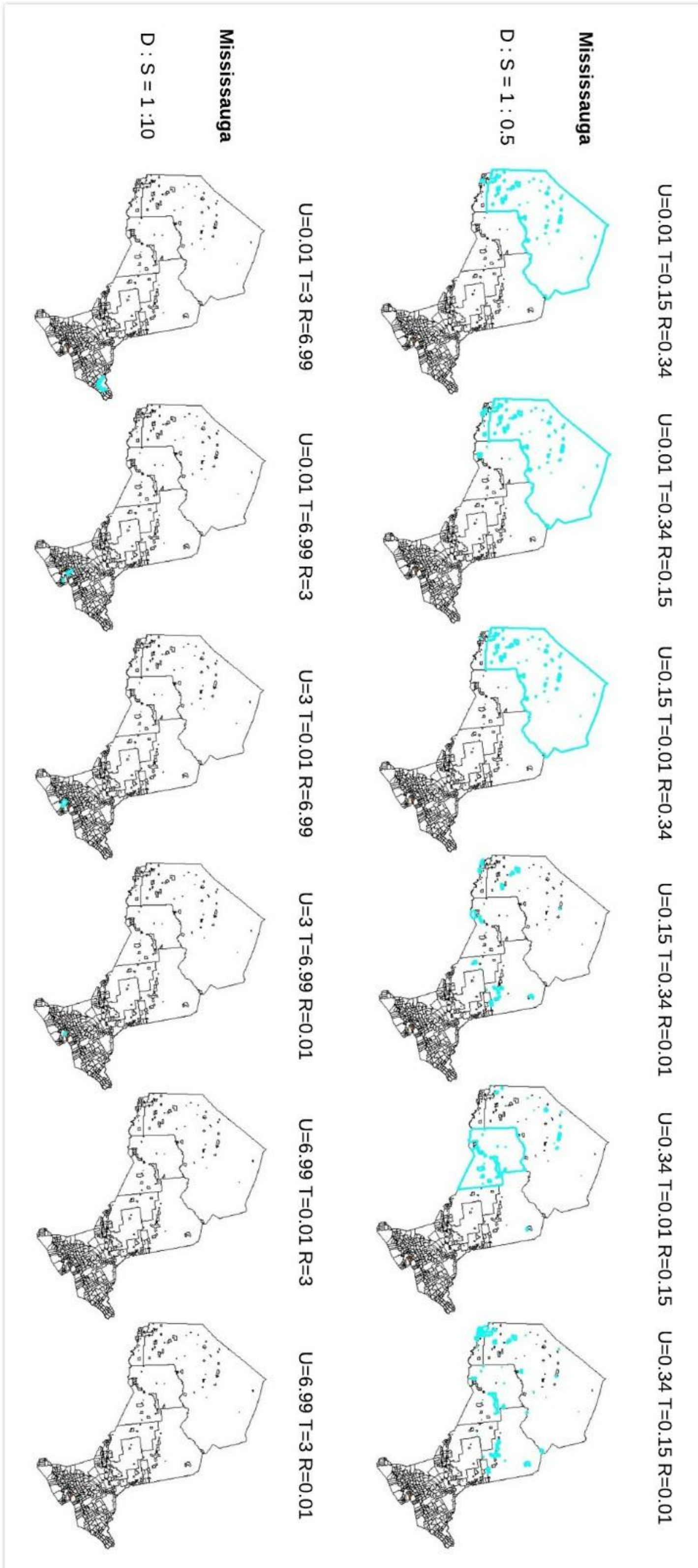

Figure 4.7: Mississauga Electricity Suppliers Small Multiples

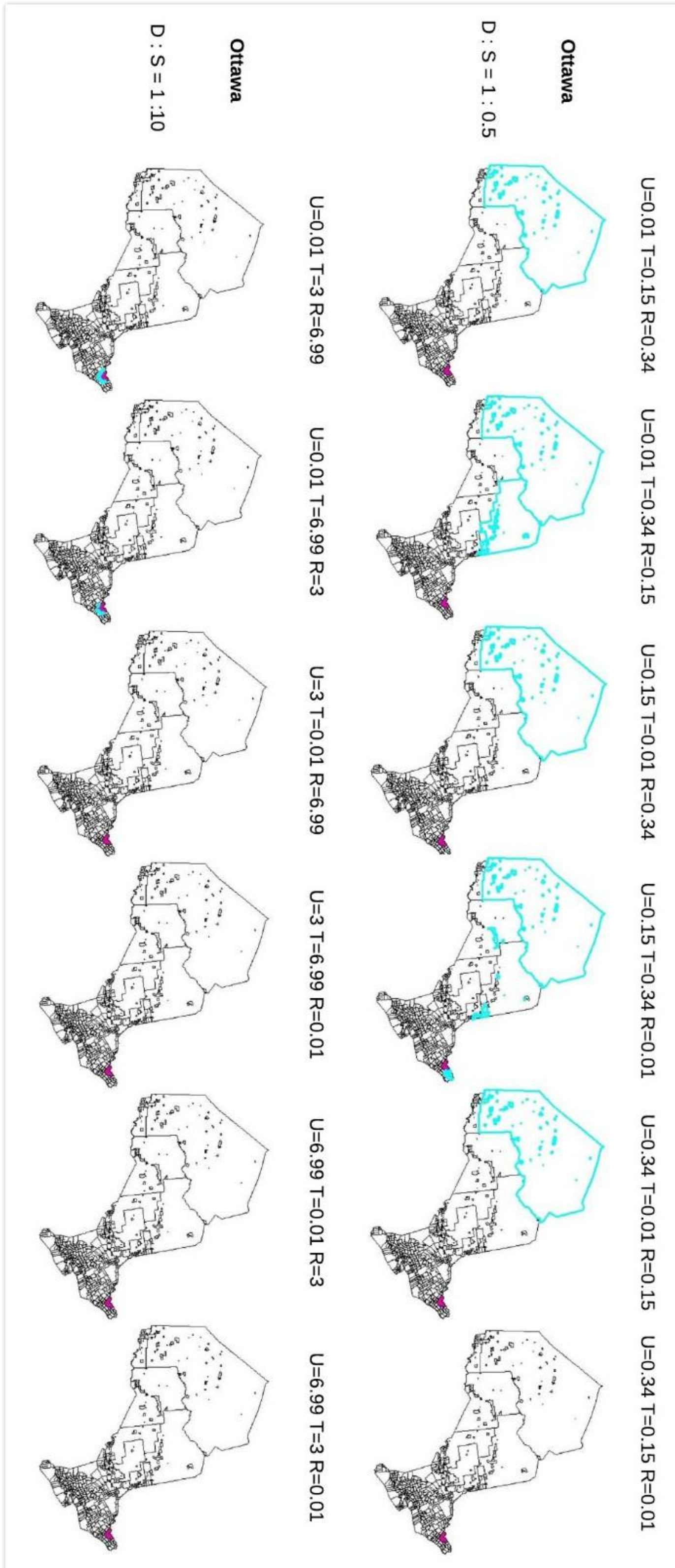

Figure 4.8: Ottawa Electricity Suppliers Small Multiples

4.4 Optional Parameters Function Illustration

4.4.1 Distance Cap

As described in Chapter 3, *Distance Cap* is an optional parameter that is created in the energy deficit-surplus matching tool. It is a user-defined distance limit to restrict energy matching calculation only within the defined distance (e.g. 200 km). The analysis presented in this section is based on a preset distance cap of 200 km for illustration of this function. Figure 4.9 and 4.10 are Toronto and Ottawa electricity supplier distributions both with and without the distance cap. From Figure 4.9 it can be seen that the left electricity supplier distribution of Toronto extends to the northern Ontario, while the right electricity supplier distribution is limited to the southern part, within the distance cap of 200 km. Within this distance limit, 28.4% of Toronto's demand is satisfied according to the energy deficit-surplus matching tool generated results. In Figure 4.10 a similar pattern applies to Ottawa, the left electricity suppliers distribution of Ottawa shows that Ottawa has to go to northern Ontario for electricity suppliers without a distance cap because big deficit CSDs such as Toronto have absorbed all nearby electricity suppliers. In the right electricity supplier distribution, Ottawa does not have to go north, but gets suppliers from surrounding surplus CSDs, even though only 39.8% of Ottawa's demand is met according to the tool results. This is the expected result, which is considered to be more cost effective and fairer for some CSDs in some cases. However, the downside is the demand fractions that are satisfied within the distance cap for each deficit CSD are different and hard to manage; meaning with the extreme case, one deficit CSD may be 100% satisfied while another deficit CSD may not get any electricity suppliers within the distance cap.

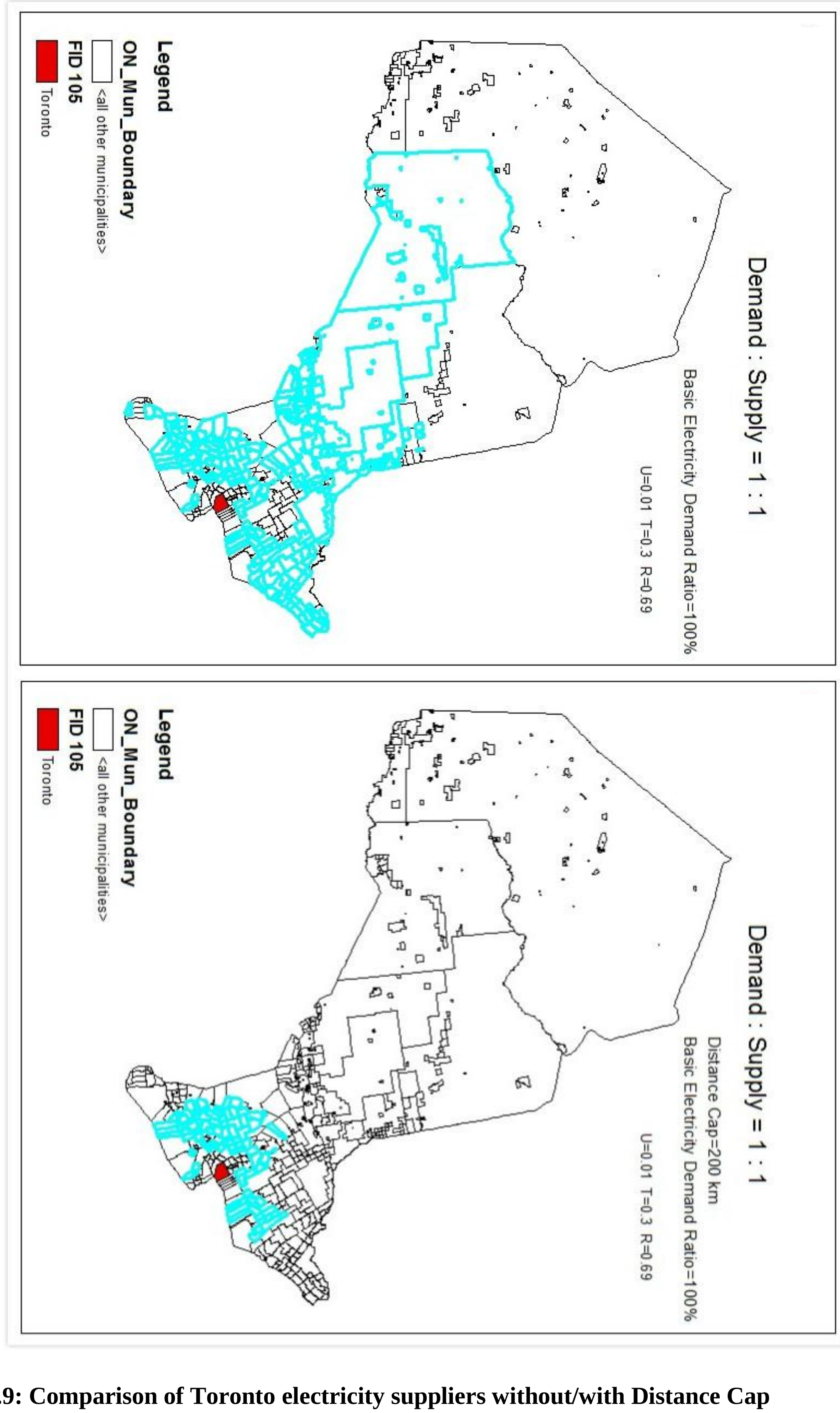

Figure 4.9: Comparison of Toronto electricity suppliers without/with Distance Cap

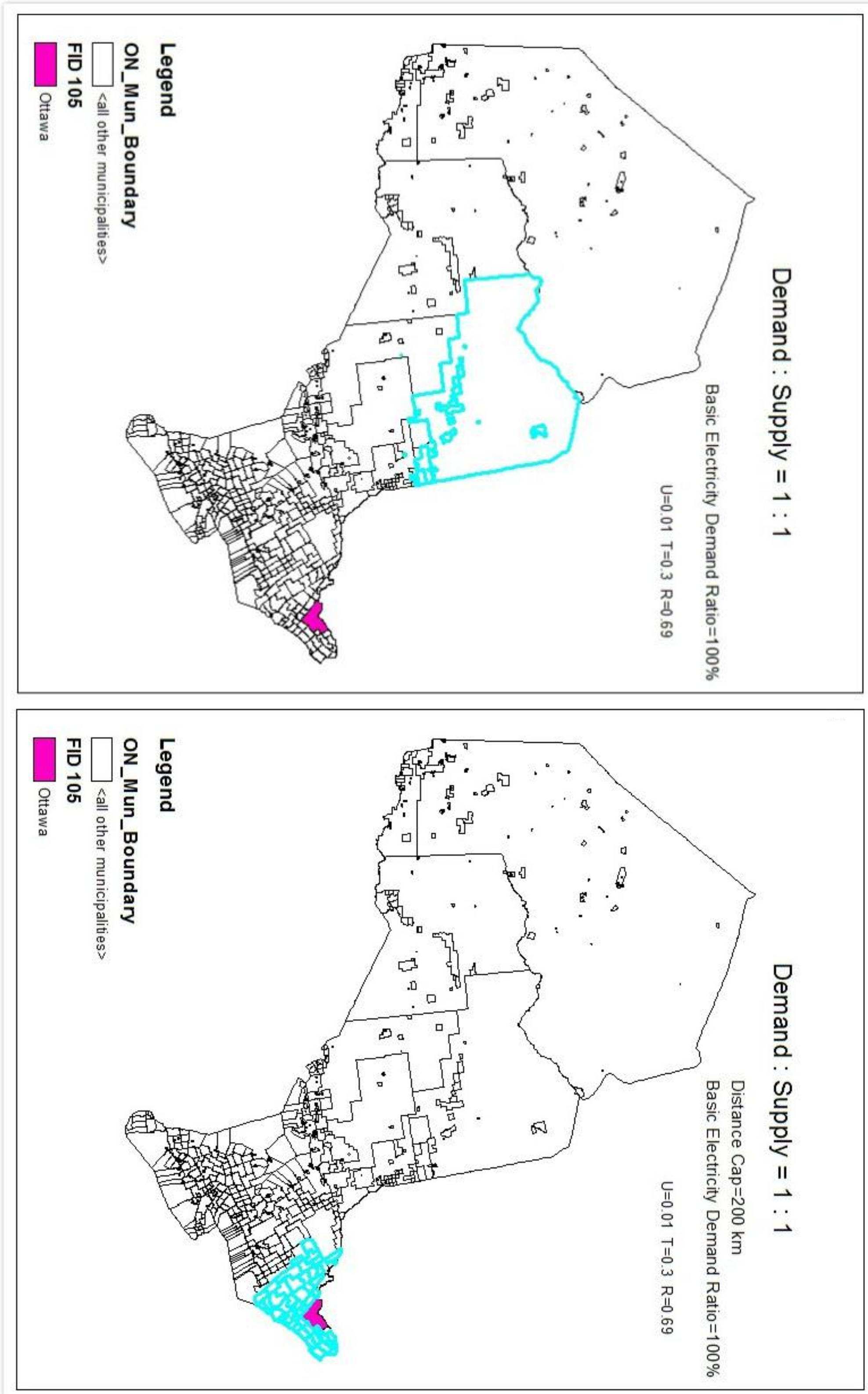

Figure 4.10: Comparison of Ottawa Electricity Suppliers without/with Distance Cap

4.4.2 **Basic Electricity Demand Ratio**

Basic Electricity Demand Ratio is also an optional parameter as defined in Chapter 3, which requires a pre-set basic electricity demand ratio for all deficit CSDs. Figure 4.11 and 4.12 show the electricity supplier distributions of Toronto and Ottawa when *Basic Electricity Demand Ratio* is set to be 100% and 57% (based on Section 3.2.6 optional parameter scenario setting description). The left illustration in both Figure 4.11 and 4.12 are when *Basic Electricity Demand Ratio* is 100% and the right illustration in each figure is when *Basic Electricity Demand Ratio* is 57%. When the *Basic Electricity Demand Ratio* is 100%, Toronto has taken most of southern electricity suppliers, which leaves Ottawa to go far north to obtain its suppliers. This may be less cost-effective as it takes longer distance for Ottawa to get electricity suppliers. On the other hand, when the *Basic Electricity Demand Ratio* is 57%, Toronto absorbs fewer southern suppliers and Ottawa is able to obtain some of its surrounding suppliers. However, as Toronto obtains fewer nearby suppliers, it has to take farther suppliers to satisfy its remaining unmet demand. Therefore, applying the *Basic Electricity Demand Ratio* option, it may be more cost effective for some deficit CSDs but the overall electricity transmission cost will increase.

Judging from the result analysis in Section 4.4, it can be found that even though *Distance Cap* and *Basic Electricity Demand Ratio* can to some degree mitigate the electricity suppliers competition/fight issues between neighboring big electricity deficit CSDs, it is not always cost-effective and most efficient for overall regional energy self-sufficiency.

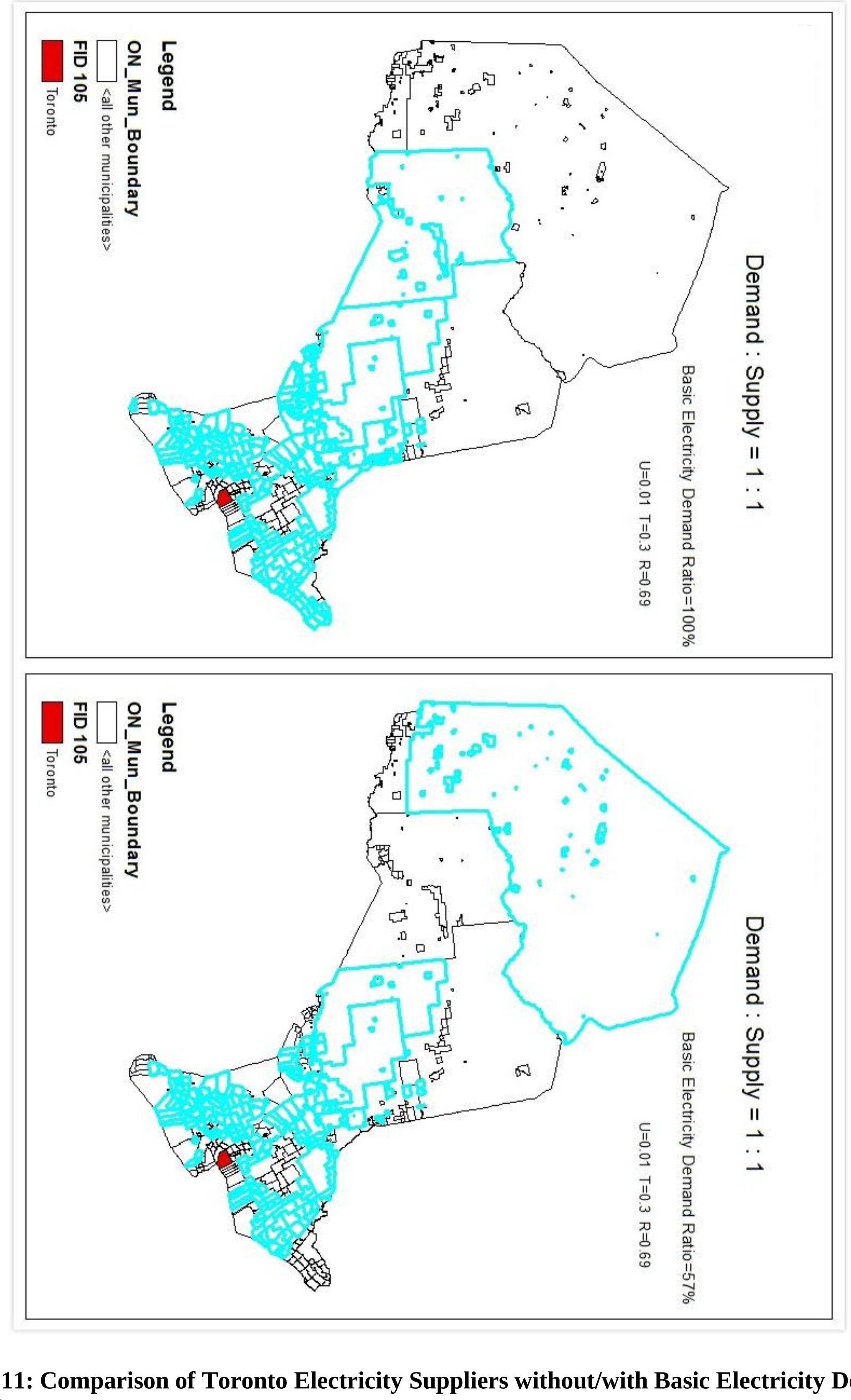

Figure 4.11: Comparison of Toronto Electricity Suppliers without/with Basic Electricity Demand Satisfaction

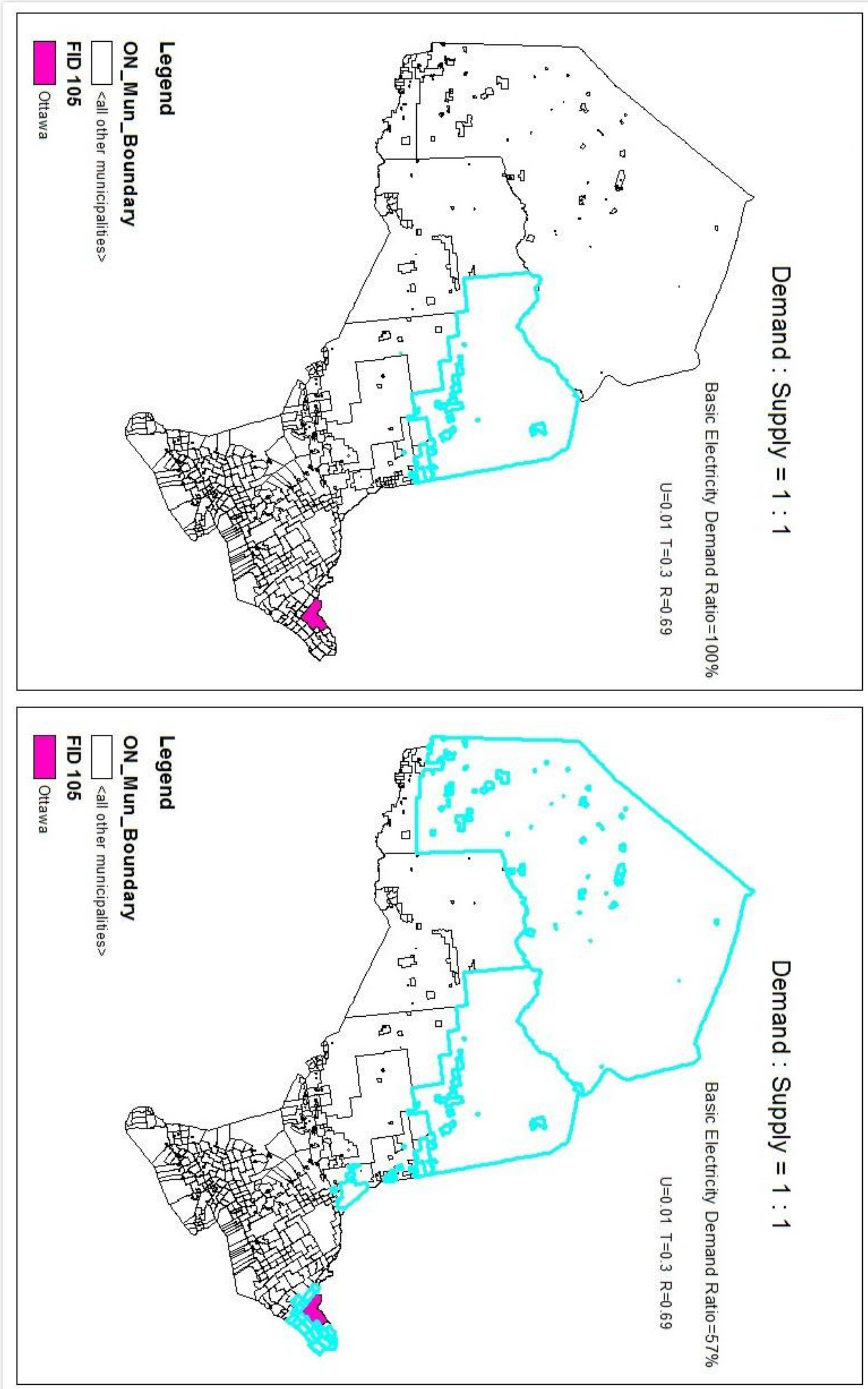

Figure 4.12: Comparison of Ottawa Electricity Suppliers without/with Basic Electricity Demand Satisfaction

4.5 Summary

This chapter summarizes and analyzes major findings from the Ontario residential electricity self-sufficiency case and two exploratory scenarios. It is concluded that it is possible for Ontario to achieve residential electricity self-sufficiency from only solar PV energy. The proposed energy deficit-surplus matching approach along with developed energy matching tool enable energy deficit CSDs within the study region with unmet energy demand to meet their demand from energy surplus CSDs in the region. Also, it is found that in Ontario case, Urban category CSDs plays a key role in affecting overall electricity supplier distributions, followed by the Town category CSDs.

Chapter 5 Conclusion & Recommendation

This chapter includes two sections. Section 5.1 reviews and summarizes the thesis research and proposed energy deficit-surplus matching methods. Results and their implications are discussed. Section 5.2 presents the limitations of this research and recommendations for future work on energy self-sufficiency research.

5.1 Conclusion

During the past decades, energy overconsumption under the prevailing centralized energy system has brought the world serious consequences such as energy resource depletion, energy-related GHG emissions, environmental degradation, and biodiversity loss. These consequences are reminding people to be more concerned with energy security and climate change issues. A transition from the current centralized unsustainable energy system to a decentralized, more sustainable energy system is widely invoked. A decentralized energy system requires more energy conservation as well as more deployment of dispersed renewable energy sources, which is closely linked to spatial land use planning.

Rooted in urban metabolism theory and an energy self-sufficiency vision, and inspired by the city-hinterland relationship, this thesis gives an introduction to a novel approach for achieving regional energy self-sufficiency through energy deficit-surplus matching, in order to tackle the current energy security and climate issues. The developed energy deficit-surplus matching methods have been applied to the selected case study region of the Province of Ontario, Canada for achieving residential electricity self-sufficiency through solar PV energy supply. The goal was to answer two research questions raised in this thesis through the implementation of energy deficit-surplus matching in the case study region.

The proposed energy deficit-surplus matching methods link spatial (GIS) modeling with assessment of regional energy consumption and renewable energy supply potential. As such it represents an important methodological advance in understanding the possible future deployment of renewable energy in decentralized ways by illustrating the identification of possible energy suppliers (energy surplus areas). In addition, the introduced methods also provide the unique advantage of comparing multiple energy deficit-surplus matching results under various energy supply-demand relation scenarios. Overall, the proposed energy deficit-surplus matching methods could serve as a decision-support tool for urban/energy planners and policy makers in building new cities, locating/relocating energy generation facilities and infrastructure, building transmission & distribution lines and networks, developing sustainable energy systems, as well as modeling future urbanization trends and predicting their influence on future energy supply-demand relations. In the long run, this tool could also help designing sustainable landscapes, ensure energy supply security, and more importantly, it could help mitigate climate change issues resulting from fossil fuel combustion. The ultimate goal is to achieve an energy self-sufficient world through the implementation of energy deficit-surplus matching.

A summary of key findings from case study is as follows:

- It is technically feasible to achieve Ontario residential electricity self-sufficiency under current solar PV technology and available PV land use occupation. However, the distinct geographical characteristics of Northern and Southern Ontario (major large urban centers situate in the south, while vast rural land occupies the north), has created a skewed distribution of electricity deficit and surplus CSDs in the study region. Also, as large urban electricity deficit CSDs such as Toronto and Mississauga are situated very close to each other, this has caused competition for nearby electricity suppliers. Generally, the vast rural areas in the North serve as distant electricity suppliers. It can be deduced that the energy deficit-surplus matching concept would work with less conflicts in a region with more dispersed energy deficit areas, where each deficit area could get its energy supply from surrounding or nearby surplus areas.

- Despite residential electricity self-sufficiency being achieved within the study region as a whole, there are still CSDs in the region that have an energy deficit (with unmet energy demand). For those energy deficit CSDs, they go to surrounding Town CSDs (towns, villages, and townships) as well as Rural CSDs to find surplus energy to meet their energy demand. The proposed methods illustrate how this surplus – deficit matching process works.

- Urban, Town, and Rural CSDs, as defined in the methods chapter, play important roles in affecting energy deficit-surplus matching results under different supply-demand relations. Under the self-sufficiency case, as well as two exploratory extreme supply-demand relation scenarios, Urban CSDs play the most important role in meeting electricity demand and minimizing need for electricity suppliers. In most cases, Urban CSDs have more electricity demand, but less space devoted for renewable energy generation than Town and Rural. So Urban areas need surrounding CSDs, as well as Town and Rural CSDs for electricity suppliers—a solution which is counter to the idea of self-sufficiency (i.e., meeting electricity demand within the urban boundary). Therefore, maximizing Urban electricity self-supply would minimize the need for external suppliers. In fact, the idea of energy matching can be extended to urban-only level, as some urban CSDs have the potential to be energy self-sufficient through utilizing urban vacant space as well as incorporating renewable energy development into urban planning practices. The Town CSDs (towns, villages, townships) is the second most important in contributing to energy matching results, since the Town category CSDs are usually located closer to Urban category CSDs, which makes them more easily accessible as energy suppliers for Urban CSDs. Rural CSDs (Reserve, Indian reserve, Unorganized areas) are least important in energy deficit-surplus matching mainly because they are usually located farther from Urban CSDs, despite the fact that Rural has the most supply potential with its vast space and lower population density. To sum up, based on the case study, the most direct way to reach self-sufficiency is to increase Urban self-supply to meet demand. The less direct way is to go to Rural areas for energy surplus areas since that would involve more use of expensive transmission infrastructure and achieves regional self-sufficiency at the cost of excessive sub area dependence.

5.2 Recommendations

Based on findings from the case study, some recommendations can be made for decision makers and urban/energy planners from the political, economic, and technological perspective.

- It is very important that urban and energy planners keep the energy deficit-surplus matching idea in mind when making energy and urban planning decisions. Under the ongoing rapid urbanization process, urban expansion and renewal present great opportunities to incorporate energy deficit-surplus matching idea in the urban planning process and decisions to build new more sustainable and self-sufficient cities.

- Policy support and public cooperation is crucial for achieving regional energy self-sufficiency through energy matching because using energy surplus areas as suppliers for energy deficit areas involves dealing with different jurisdictions (e.g., community, district, city, municipal level), which would be simplified with strong policy support. Besides, good policies would help promote achieving energy self-sufficiency through energy deficit-surplus matching, which to some degree could motivate the general public and all stakeholders to get involved. Public cooperation is very important in developing renewable energy deficit-surplus matching projects, as it would affect land use decisions in terms of establishing energy facilities and infrastructure. Public support and cooperation would tremendously contribute to the success of achieving regional energy self-sufficiency, while public opposition would complicate and delay this important energy system transition.

- Technological considerations are major part of the energy deficit-surplus matching process. An important feature of energy deficit-surplus matching is that it requires local renewable energy distribution via transmission infrastructure in the region. Technology improvements and inventions in renewable energy storage, transmission & distribution could have a great impact on realizing energy deficit-surplus matching results. Also, apart from solar PV energy, more renewable energy technologies such as wind power; heat pumps, and geothermal systems, biomass, use of sewage and methane capture could be potential energy supply sources.

- Financial support must be available. As a novel spatial energy solution, energy deficit-surplus matching deals with various renewable technologies, land use requirements, spatial and energy data acquisition, and transmission lines issues all of which are complicated real-world situations that cost a great deal of money and labor. Financial support (e.g., tariff, allowance, rebates, and credits) is very helpful to get the energy deficit-surplus matching process started.

In conclusion, the vision of achieving energy self-sufficiency through energy deficit-surplus matching includes not only opting for renewable sources of energy, but also efficient, economical, and innovative use of renewable energy. Spatial energy planning is one of the core elements of this vision. In the foreseeable future, distributed generation of renewable energy, and Urban, Town as well as Rural areas all have a central role in contributing to achieving regional energy self-sufficiency.

Although this research was carefully prepared and has reached its aims, there are some unavoidable limitations and shortcomings. First, due to time constraints, this research was conducted only at the Ontario scale. The proposed methods are intended to be applicable over any spatial unit, and the geographical characteristics of Ontario do not allow an illustration of the entire scope of these methods. Also, only residential electricity consumption and solar PV energy were considered. There would likely be different results if commercial or industrial electricity consumption were considered with other RES supply such as wind and geothermal energy. Second, due to a lack of available and/or reliable data for the case study, assumptions on PV energy density and PV land occupation fraction had to be made to complete the research. This might increase uncertainty, and was the main driver for the sensitivity analyses described above. Third, this research focuses on exploring the feasibility of achieving energy self-efficiency through energy deficit-surplus matching without considering technical, financial, social, and political factors. Finally, since the idea of energy deficit-surplus matching is novel, we await future work and other researchers to provide guidance on validating and modifying the method.

Thus, future work is expected to focus on improving the methods of energy deficit-surplus matching and GIS linkage to generate more spatial insights on energy matching. Modifications are needed to the proposed methods by: a) extend the research scale beyond the Ontario context to bigger scales such as provinces, national-wide, or smaller scales to various districts, economic regions, cities, communities. Multiple scales would help illustrate the methods and allow comparisons of energy deficit-surplus matching patterns. b) The use of more accurate data input to the energy deficit-surplus matching tool for further sensitivity analysis on self-sufficiency and energy deficit-surplus matching results under various supply-demand relation scenarios. c) Apply more suitable methods in measuring/estimating energy consumption in residential, commercial, industrial and institutional sectors. The energy deficit-surplus matching tool also has the potential to be adapted to other applications such as wind power, geothermal, hydro, biomass, and tidal renewable energies. Supply potential research can be done on these renewable technologies individually and also in supply combinations. d) As mentioned in this thesis that there are two deficit-surplus matching methods, and two corresponding algorithms have been provided for developing the energy deficit-surplus matching tool, but only one was illustrated. Further research can compare these two matching methods, and provide insights on the advantages and disadvantages of each. e) In order to make the energy deficit-surplus matching methods more flexible and applicable in the real world, more considerations regarding political, economic, technical and social factors could be added to the method’s design. f), theoretical research on energy self-sufficiency should also be explored and updated due to its significance in guiding the energy deficit-surplus matching methods.

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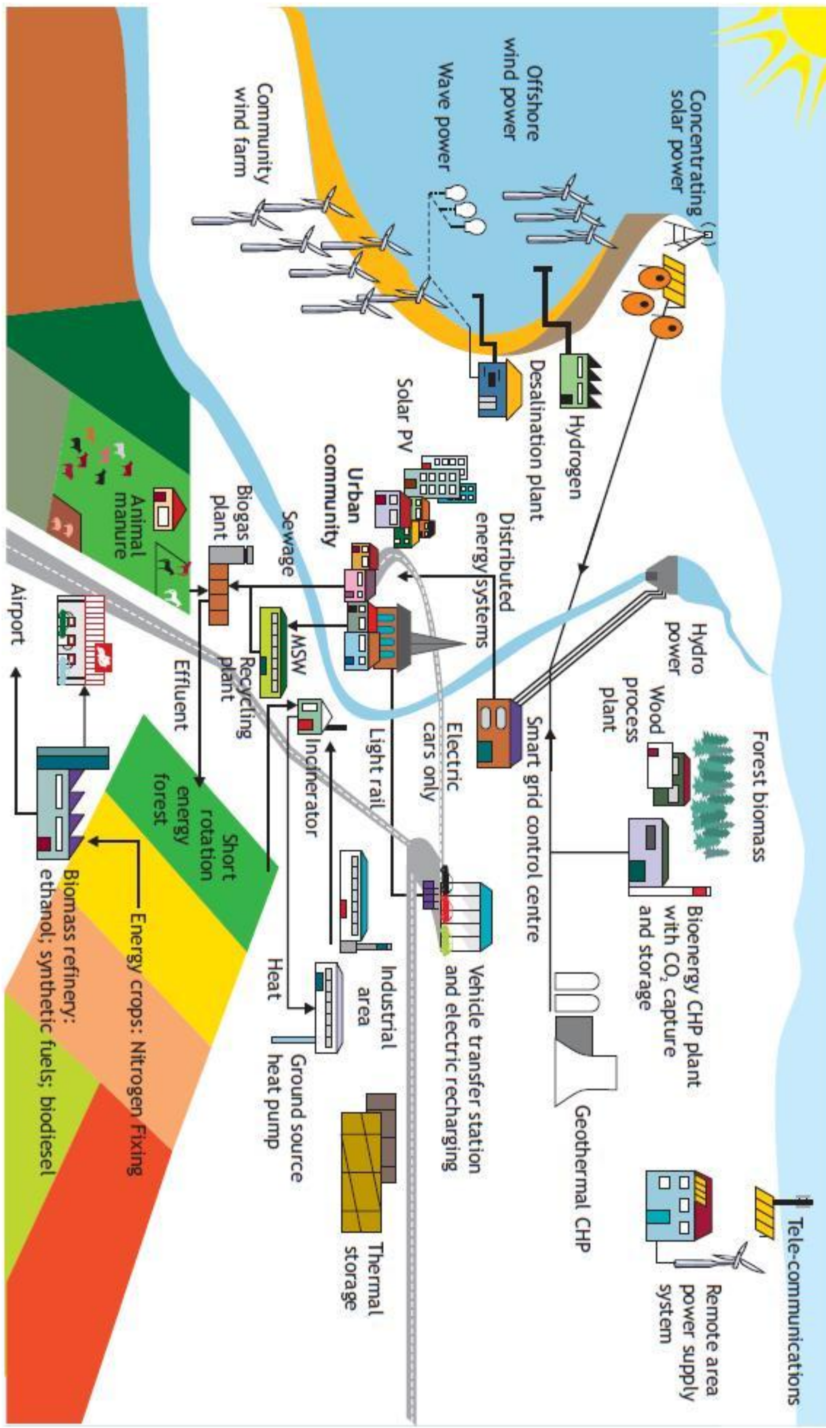
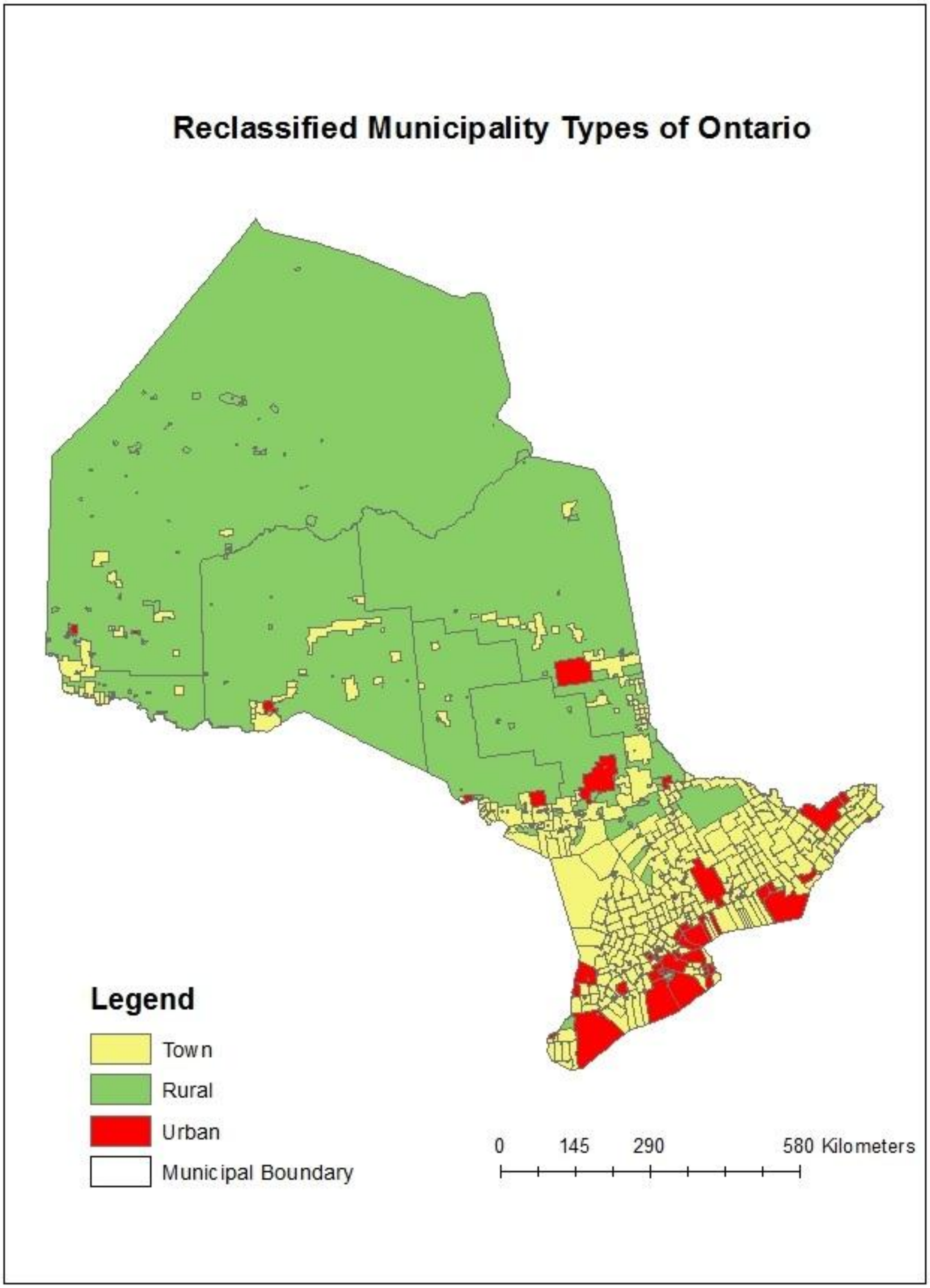
Appendices

Appendix I: An Example of Urban Area Power by Renewable Energies



Source: (International Energy Agency, 2009)

Appendix II: A Map of Reclassified Municipality Types of Ontario



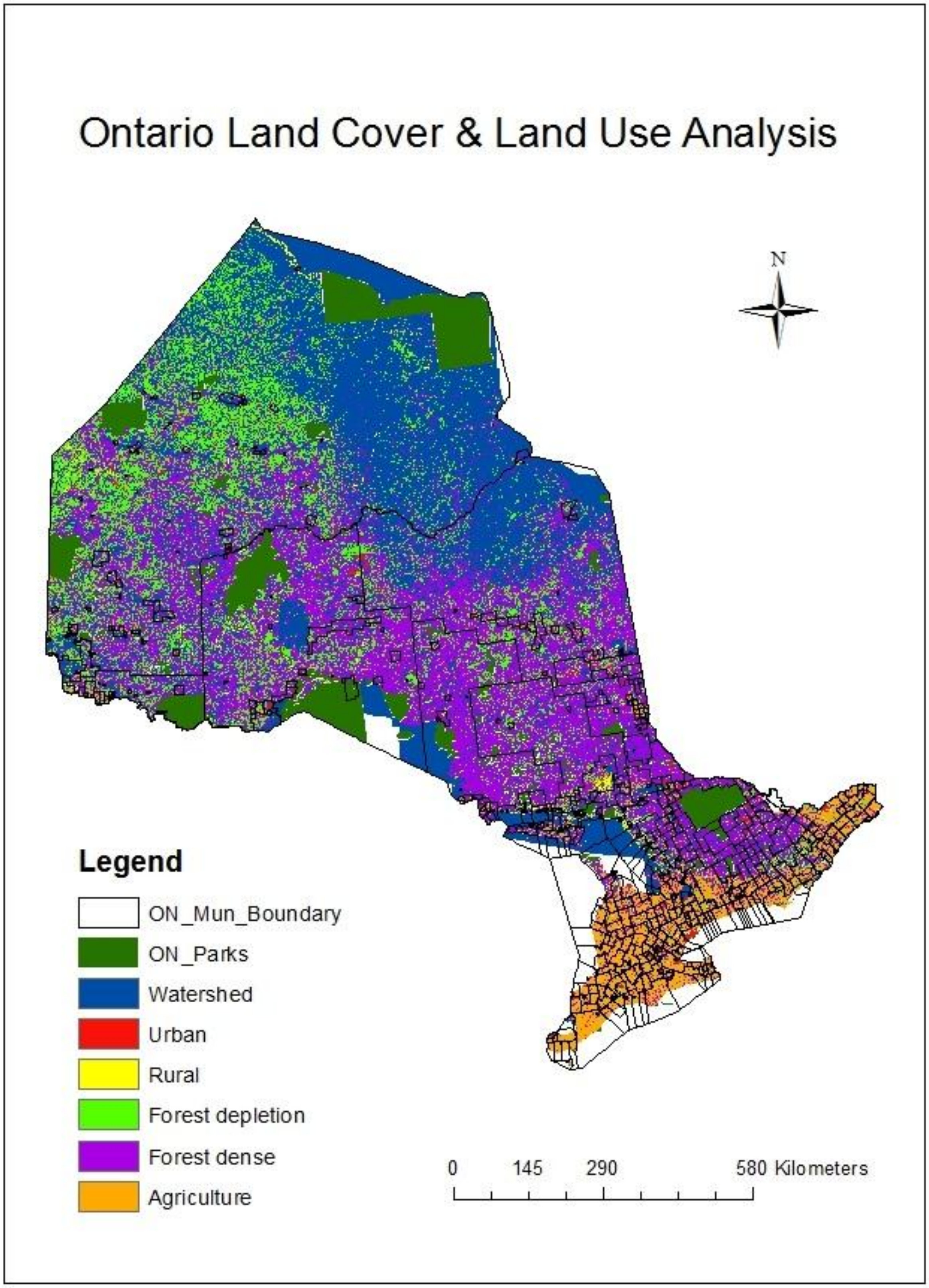
Appendix III: Ontario and Michigan Annual Solar Radiation

Ontario Climte data location	Annual solar radiation-horizonal (kWh/m2/d	Michigan Climte data location	Annual solar radiation-horizonal (kWh/m2/d
Armstrong Airport	3.36	Adrian	3.79
Atikokan (Aut)	3.43	Alma	3.71
Attawapiskat	3.32	Alpena	3.72
Bancroft Auto	3.59	Ann Arbor Municipal	3.51
Barrie (MARS)	3.52	Antrim Co Arpt	3.65
Beausoleil	3.52	Bad Axe	3.68
Belle River	3.64	Battle Creek Kellogg Ap	3.5
Big Trout Lake	3.27	Benton Harbor/Ross	3.6
Big Trout Lake Readac	3.23	Big Rapids	3.66
Britt (MARS)	3.74	Cadillac Wexford Co Ap	3.44
Burlington Piers	3.59	Charlevoix	3.63
Caribou 1sl (MAPS)	3.54	Chippewa Intl (AWOS)	3.55
Carleton Place	3.59	Coldwater	3.76
Chapleau	3.46	Copper Harbor Ramos	3.71
Cobourg	3.65	Detroit City Airport	3.53
Cochrane	3.37	Detroit Metro Ap	3.78
Collingwood	3.61	Detroit Willow Run Ap	3.58
Cover Island (MAPS)	3.74	Escanaba (AWOS)	3.61
Deep River	3.5	Flint	3.72
Dryden	3.47	Gaylord	3.61
Earlton Airport	3.62	Grand Rapids	3.8
Egbert	3.68	Grosse Isle Arpt	3.73
Elliot Lake	3.51	Hancock Houghton Co Ap	3.35
Elora Rcs	3.67	Harbor Beach (Ramos)	3.86
Erieau (MAPS)	3.6	Hillsdale	3.76
Geraldton Airport	3.44	Holland	3.92
Goderich (Aut)	3.64	Holland/Tulip City	3.8
Gore Bay Airport	3.83	Houghton Lake	3.56
Great Duck Island	3.73	Howell	3.69
Grenadier Island	3.57	Iron Mountain	3.6
Guelph	3.71	Iron Mountain/Ford	3.41
Hamilton A	3.74	Iron River	3.57
Hearst	3.39	Ironwood (AWOS)	3.54
Huntsville	3.55	Jackson Reynolds Field	3.44
Kapuskasing Airport	3.48	Kalamazoo Battle Cr	3.48
Kenora Airport	3.72	Lansing	3.76
Kilarney (MAPS)	3.74	Lapeer	3.67
Kingston	3.56	Ludington/Mason	3.67
Kirkland Lake	3.41	Manistee (AWOS)	3.56
Lagoon City	3.52	Manistique	3.58
Lansdowne House	3.32	Marquette County Arpt	3.22
London Airport	3.79	Marquette Sawyer AFB	3.59
Long Point (MAPS)	3.75	Marshall Brooks	3.74
Manitouwadge	3.4	Mason	3.72
Marathon	3.61	Menominee (AWOS)	3.62
Mattawa	3.5	Monroe	3.77
Moosonee (Sawr)	3.19	Mount Clemens Selfridge F	3.54
Mount Forest (MARS)	3.66	Mt Pleasant Muni	3.7
Muskoka Airport	3.81	Munising	3.61
Nagagami (MARS)	3.4	Muskegon	3.83
North Bay Airport	3.66	Newberry	3.46
Ottawa Int'l Airport	3.59	Newberry Luce Co.	3.63
Owen Sound	3.61	Northview	3.72
Peawanuck (MAPS)	3.21	Ontonagon	3.57
Petawawa A Ont	3.59	Oscoda Wurtsmith AFB	3.64
Peterborough A	3.53	Pellston Emmet County Ap	3.31
Pickle Lake (Aut)	3.31	Pontiac-Oakland	3.43
Point Petre (MARS)	3.75	Rock Of Ages	3.67
Port Colborne (Aut)	3.62	Saginaw Tri City Intl Ap	3.47
Port Weller (MARS)	3.59	Sault Ste. Marie	3.67
Pukaskwa (Aut)	3.61	Sawyer Intl	3.57
Red Lake Airport	3.32	Seul Choix Pt (Amos)	3.63
Royal Island (Aut)	3.49	St. Clair County Int	3.65
S.E. Shoals (MAPS)	3.77	Stannard Rock	3.71
ault Ste. Marie Airpor	3.69	Sturgis\Kirsh Muni	3.78
Simcoe (MARS)	3.8	Traverse City	3.65
Sioux Lookout Airport	3.62	Aveage	3.63
Sudbury	3.55		
Sudbury Airport	3.68		
Terrace Bay	3.61		
Thessalon	3.51		
Thunder Bay Airport	3.78		
Timmins Airport	3.54		
Toronto	3.59		
Toronto Buttonville	3.59		
Toronto II Arpt Aut	3.59		
Toronto Int'l Airport	3.67		
Trenton Airport	3.56		
Upsala (MARS)	3.44		
Wawa Airport	3.54		
Welcome Island (Aut)	3.48		
Western Isl (MAPS)	3.74		
Wiarton Airport	3.85		
Windsor Airport	4.03		
Ave	3.57		

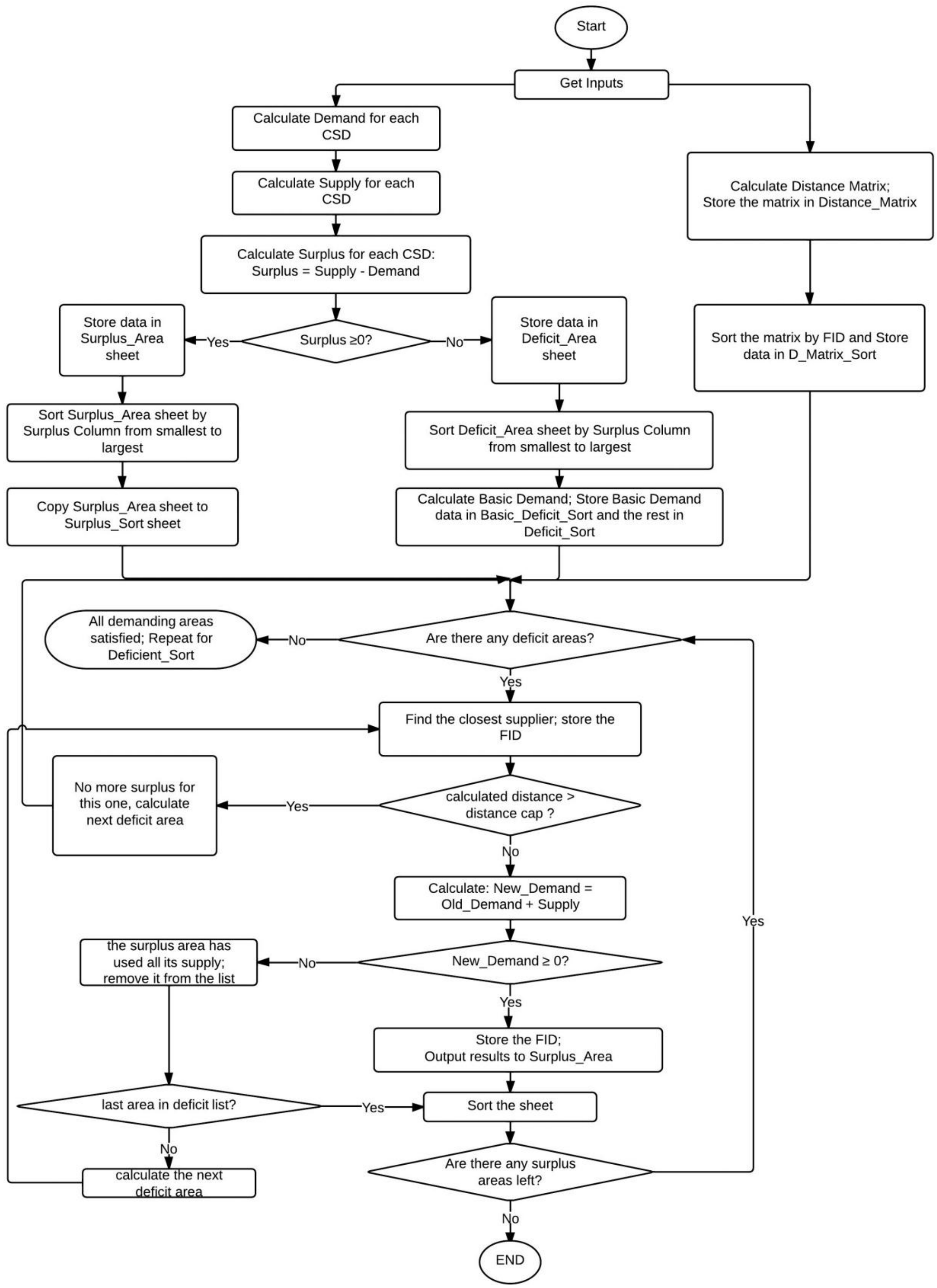
Appendix IV: Reclassification of Provincial Land Cover Classes

Map Name	Provincial Landcover 2000 - 27 Classes	Southern Ontario Canada Land Inventory Land Use	Reclassification
Description	• Producer: Ontario Ministry of Natural Resources • Date published: 1999-07-11 (creation), 2002-08-31 (revision) • Type of data layer: Raster • Coordinate system: 4269 - "NAD83" 	• Producer: Ducks Unlimited Canada • Date published: 1950-01-01 (creation), 2009-03-13 (revision) • Type of data layer: Vector • Coordinate system: 4269 - "NAD83" 	**Watershed** – 1, 2, 6, 15-23 – q, k **Urban & Unknown** – 3, 28, 29 – i, p, m **Rural** – 4, 5, 24 – n, o, f, **Forest Depletion** – 7, 8, 9, 10 – g **Forest Dense** – 11, 12, 13 – j **Agriculture** – 25, 27 – c, d, e, f, l, b, h,
Legend	1. Water - deep clear 2. Water - shallow / sedimented 3. Settlement / Infrastructure 4. Sand / Gravel / Mine Tailings 5. Bedrock 6. Mudflats 7. Forest Depletion - cuts 8. Forest Depletion - burns 9. Forest - regenerating depletion 10. Forest - sparse 11. Forest - dense deciduous 12. Forest - dense mixed 13. Forest - dense coniferous 14. Marsh- intertidal 15. Marsh - supertidal 16. Marsh - inland 17. Swamp - deciduous 18. Swamp - coniferous 19. Fen - open 20. Fen - treed 21. Bog- open 22. Bog - treed 23. Tundra Heath 24. Agriculture - Pasture / abandoned fields 25. Agriculture - cropland 26. Other - unknown 27. Other - cloud / shadow	a. Cropland - 50.0% - 74.9% b. Horticulture c. Improved pasture and forage crops - 50.0% - 74.9% d. Improved pasture and forage crops - 75.0% - 94.9% e. Improved pasture and forage crops - 95.0% - 100.0% f. Mines, quarries, sand and gravel pits g. Non-productive woodland h. Orchards and vineyards i. Outdoor recreation j. Productive woodland—forest k. Swamp, marsh or bog l. Unimproved pasture and range land m. Unknown n. Unproductive land – rock o. Unproductive land – sand p. Urban built-up area q. Water area	

Appendix V: A Map of Land Exclusions for Ontario Case Study



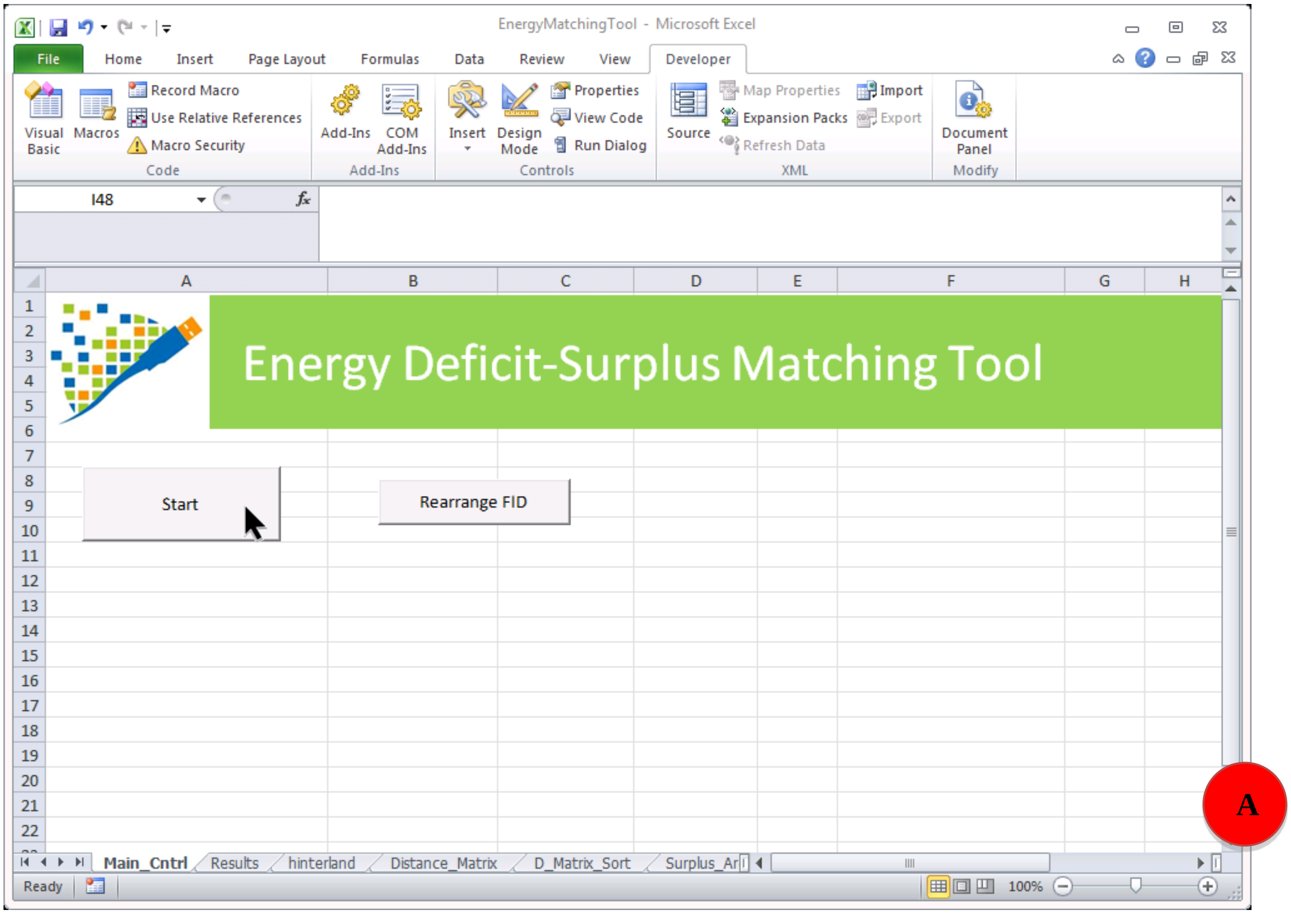
Appendix VI: Alternative Algorithm of Energy Deficit-Surplus Matching Tool



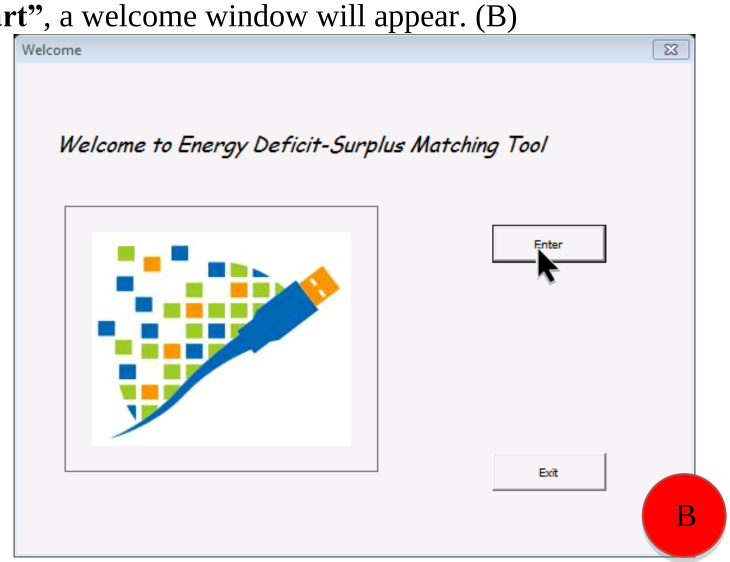
Appendix VII: Energy Deficit-Surplus Matching Tool Guide

Import Data

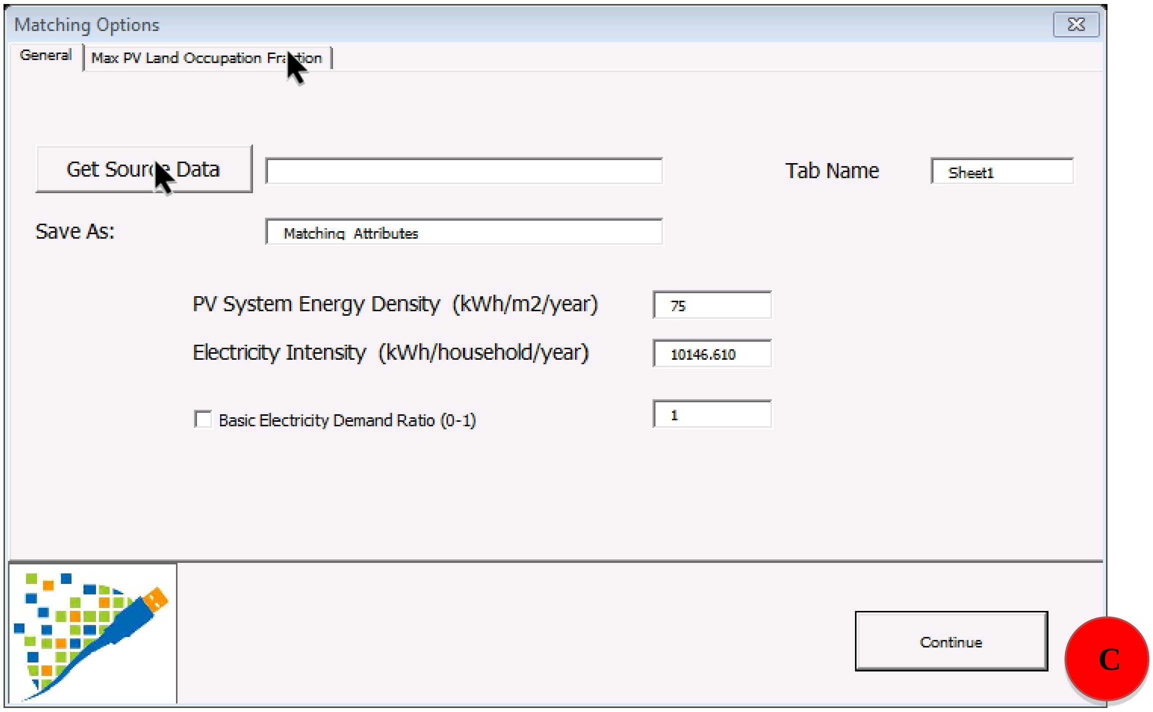
1. Open Energy Deficit-Surplus Matching Tool.xlsm. (A)



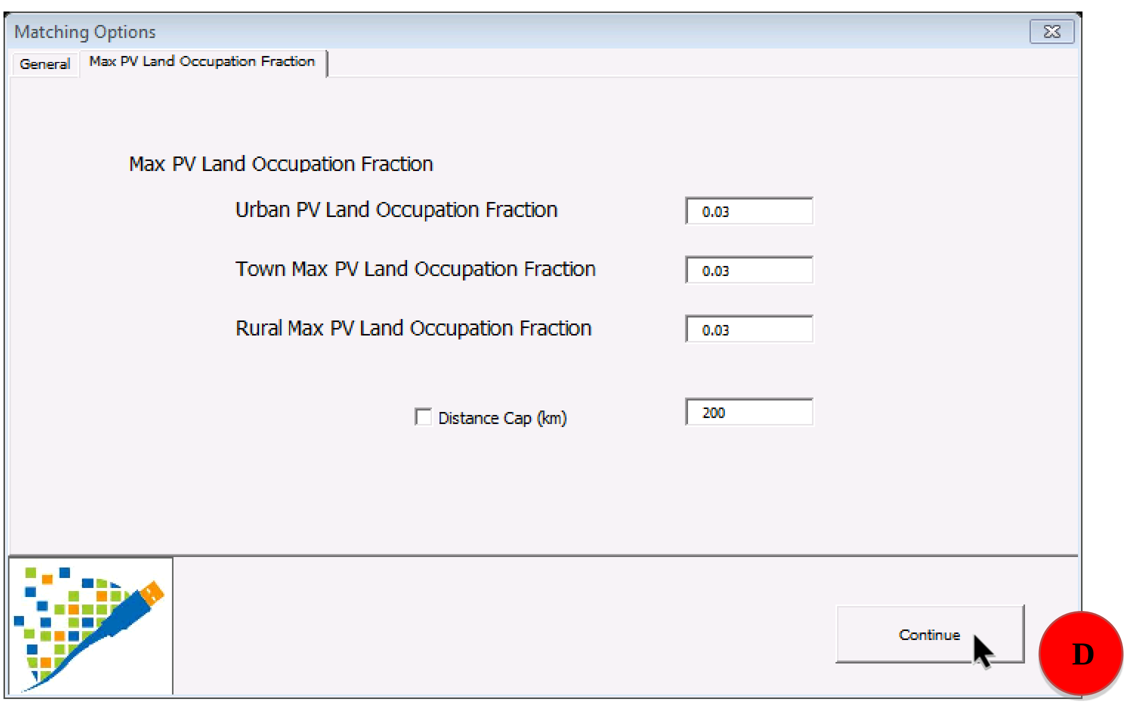
2. Click on “**Start**”, a welcome window will appear. (B)



3. Click "**Enter**" and get into "Matching Options" window. (C)
4. Click on "**Get Source Data"**. Select a file to attach. Select Open. Enter Tab Name, and "Save As" text boxes.



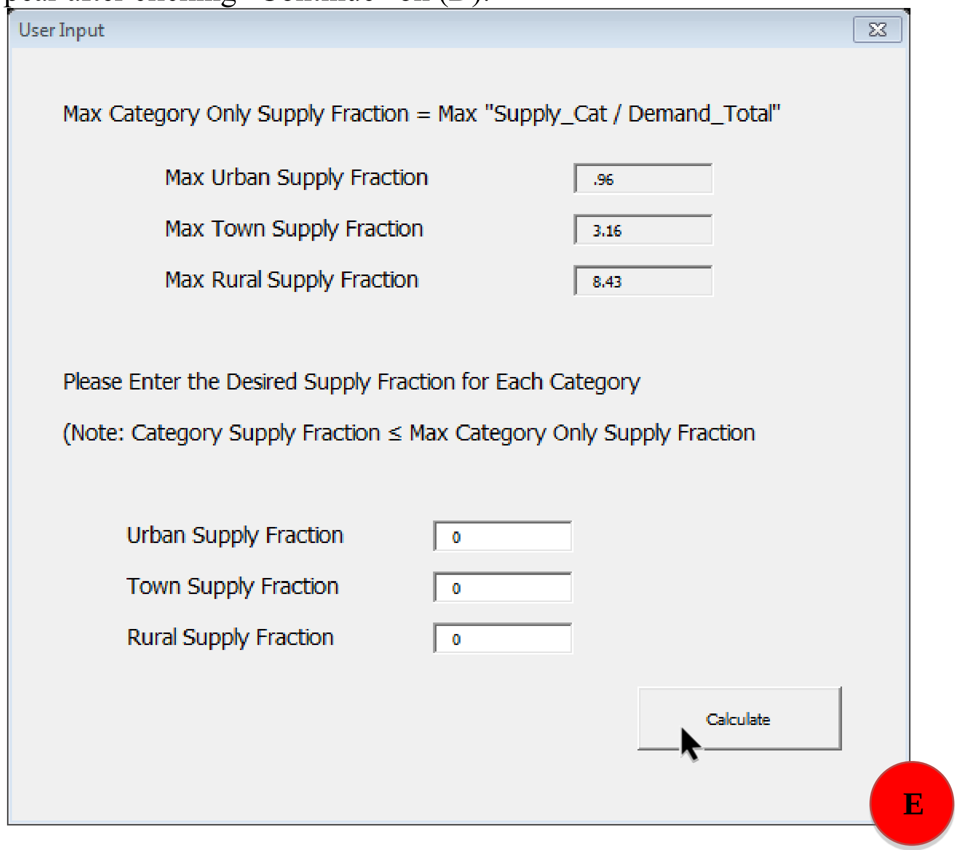
5. Enter values for parameters: PV system energy density, Electricity Intensity, and Basic Electricity Demand Ratio.
6. Click "**Max PV Land Occupation Fraction**" option. See (D)



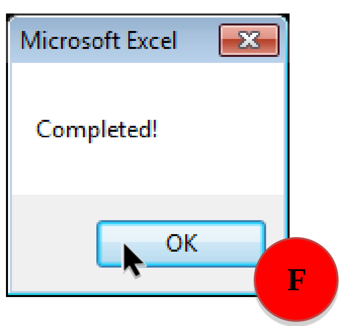
7. Enter values for category Max PV land occupation fraction.
8. Check "**Distance Cap**" if needed, and enter desired value.
9. Click "**Continue**". (D)

Manually Entering Parameter Values

1. (E) will appear after clicking "Continue" on (D).

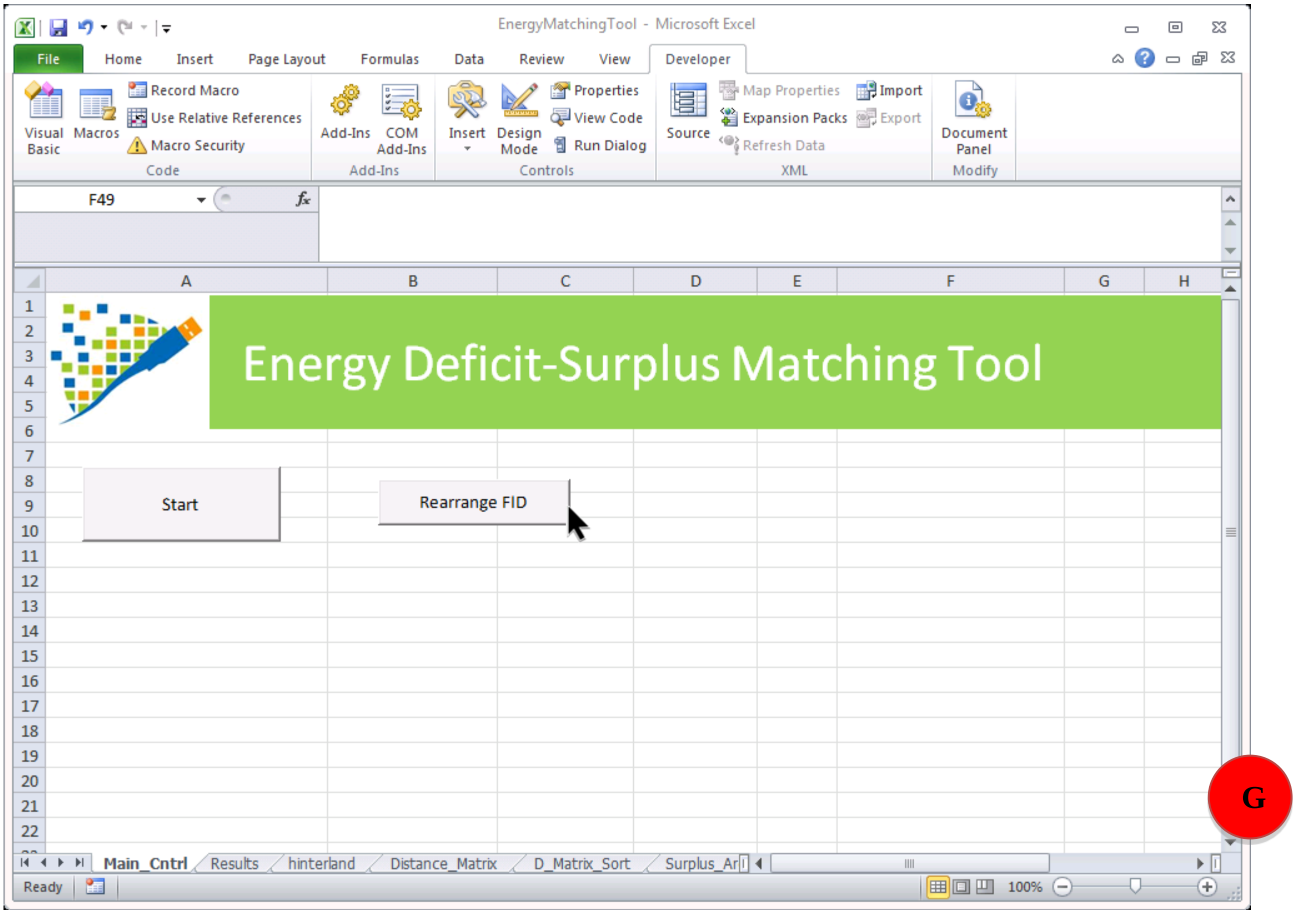


- Enter appropriate values in the User Input window
- Click "**Calculate**", run the tool. (F) will appear when calculation finished.

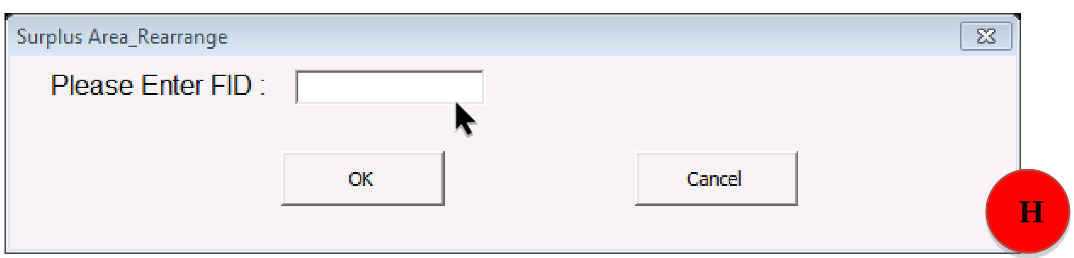


Generating Results

1. Click "**Rearrange FID**" on (G) a "Surplus Areas Rearrange" window (H) will appear.

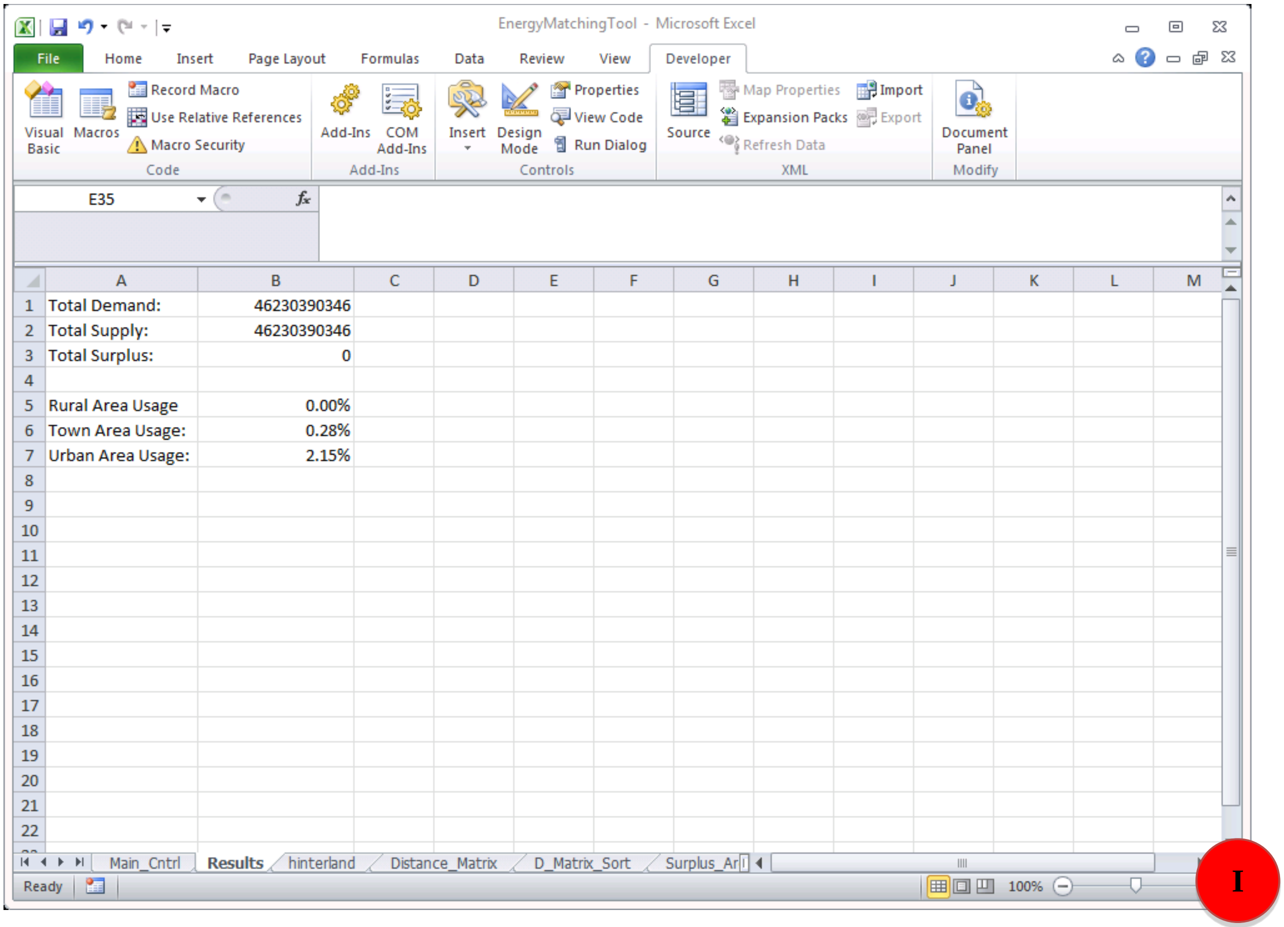


2. Enter a Field ID for desired CSD. (H)



3. An export csv. File will be generated on the same folder with EnergyMatchingTool.xlsm.

4. Total demand, total supply, total surplus, Area usage of Urban, Town and Rural; as well as supply rate (if selected distance cap) will be displayed on Results sheet on (I)

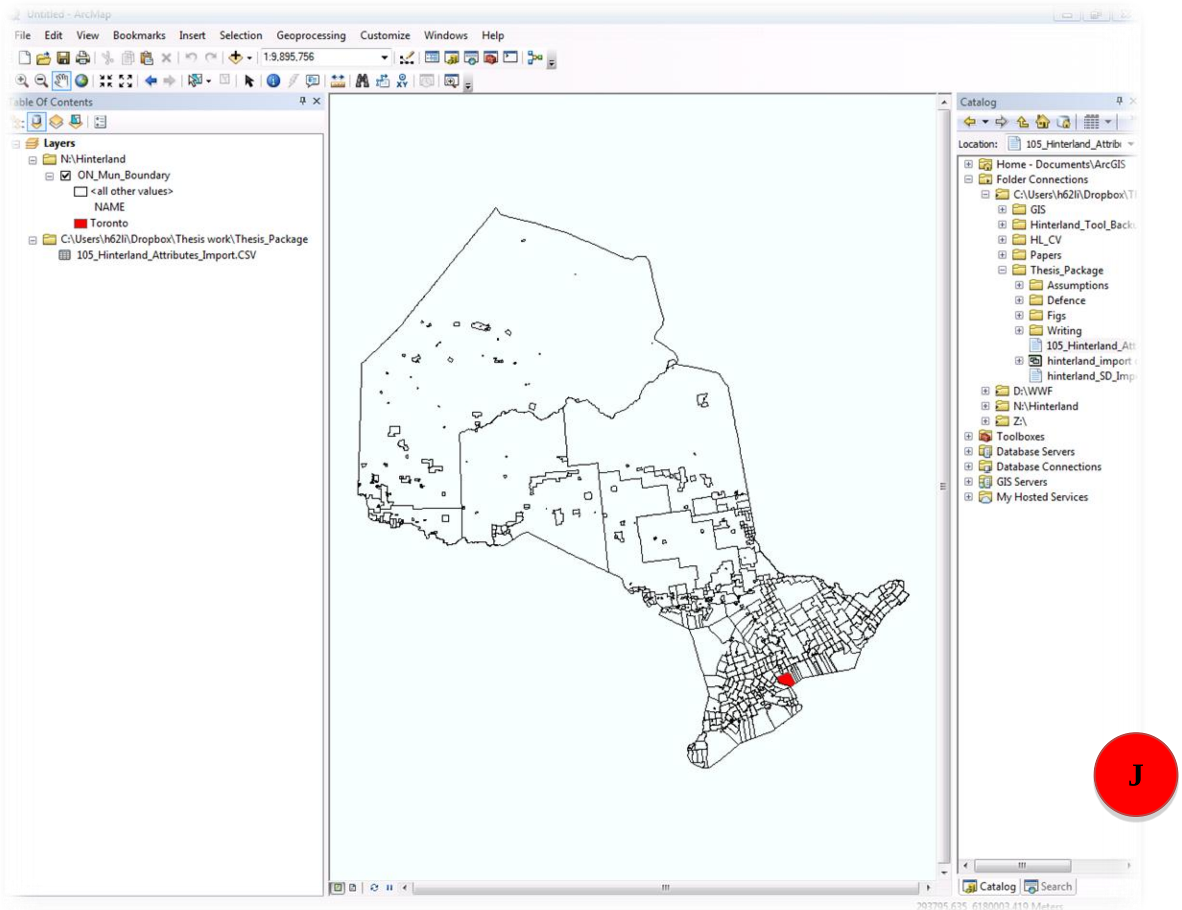


Importing Results to ArcGIS

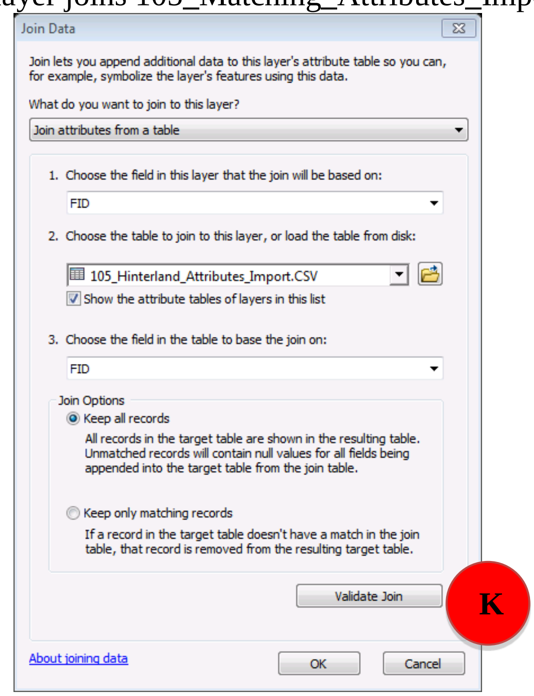
1. Have base boundary map of the study region (Ontario in this case) readily displayed in ArcGIS. (J)

2. Highlight picked CSD on the base map (e.g. Toronto (FID-105) is highlighted as RED in (J).

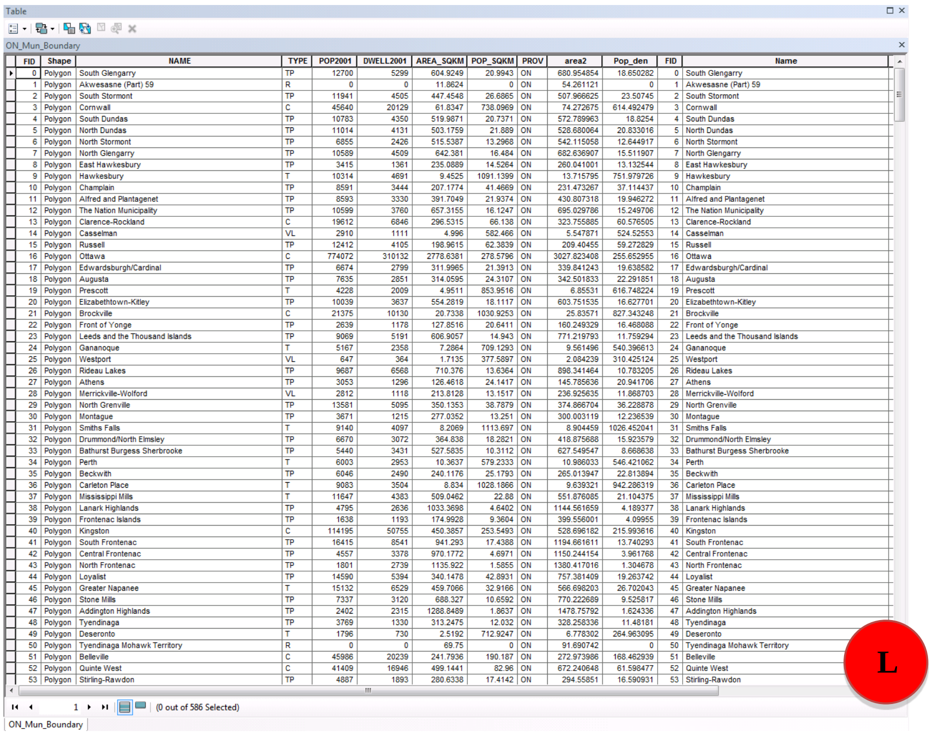
3. Import energy matching result (e.g. 105_Matching_Attributes_Import.CSV) into ArcGIS. (J)



4. Join study region base map to energy matching result file by FID (e.g. ON_Mun_Boundary layer joins 105_Matching_Attributes_Import.CSV by FID. See (K)



5. Open Attribute Table of study region base map layer after join. (L)



Table

ON_Mun_Boundary

FID	Shape	NAME	TYPE	POP2001	DWELL2001	AREA_SQKM	POP_SQKM	PROV	area2	Pop_den	FID	Name
0	Polygon	South Glengarry	TP	12700	5299	604.9249	20.9943	ON	680.954854	18.650282	0	South Glengarry
1	Polygon	Akwesasne (Part) 59	R	0	0	11.8624	0	ON	54.261121	0	1	Akwesasne (Part) 59
2	Polygon	South Stormont	TP	11941	4505	447.4548	26.6865	ON	507.966625	23.50745	2	South Stormont
3	Polygon	Cornwall	C	45640	20129	61.8347	738.0969	ON	74.272675	614.492479	3	Cornwall
4	Polygon	South Dundas	TP	10783	4350	519.9871	20.7371	ON	572.789963	18.8254	4	South Dundas
5	Polygon	North Dundas	TP	11014	4131	503.1759	21.889	ON	528.680064	20.833016	5	North Dundas
6	Polygon	North Stormont	TP	6855	2426	515.5387	13.2968	ON	542.115058	12.644917	6	North Stormont
7	Polygon	North Glengarry	TP	10589	4509	642.381	16.484	ON	682.636907	15.511907	7	North Glengarry
8	Polygon	East Hawkesbury	TP	3415	1361	235.0889	14.5264	ON	260.041001	13.132544	8	East Hawkesbury
9	Polygon	Hawkesbury	T	10314	4691	9.4525	1091.1399	ON	13.715795	751.979726	9	Hawkesbury
10	Polygon	Champlain	TP	8591	3444	207.1774	41.4669	ON	231.473267	37.114437	10	Champlain
11	Polygon	Alfred and Plantagenet	TP	8593	3330	391.7049	21.9374	ON	430.807318	19.946272	11	Alfred and Plantagenet
12	Polygon	The Nation Municipality	TP	10599	3760	657.3155	16.1247	ON	695.029786	15.249706	12	The Nation Municipality
13	Polygon	Clarence-Rockland	C	19612	6846	296.5315	66.138	ON	323.755885	60.576505	13	Clarence-Rockland
14	Polygon	Casselman	VL	2910	1111	4.996	582.466	ON	5.547871	524.52553	14	Casselman
15	Polygon	Russell	TP	12412	4105	198.9615	62.3839	ON	209.40455	59.272829	15	Russell
16	Polygon	Ottawa	C	774072	310132	2778.6381	278.5796	ON	3027.823408	255.652955	16	Ottawa
17	Polygon	Edwardsburgh/Cardinal	TP	6674	2799	311.9965	21.3913	ON	339.841243	19.638582	17	Edwardsburgh/Cardinal
18	Polygon	Augusta	TP	7635	2851	314.0595	24.3107	ON	342.501833	22.291851	18	Augusta
19	Polygon	Prescott	T	4228	2009	4.9511	853.9516	ON	6.85531	616.748224	19	Prescott
20	Polygon	Elizabethtown-Kitley	TP	10039	3637	554.2819	18.1117	ON	603.751535	16.627701	20	Elizabethtown-Kitley
21	Polygon	Brockville	C	21375	10130	20.7338	1030.9253	ON	25.83571	827.343248	21	Brockville
22	Polygon	Front of Yonge	TP	2639	1178	127.8516	20.6411	ON	160.249329	16.468088	22	Front of Yonge
23	Polygon	Leeds and the Thousand Islands	TP	9069	5191	606.9057	14.943	ON	771.219793	11.759294	23	Leeds and the Thousand Islands
24	Polygon	Gananoque	T	5167	2358	7.2864	709.1293	ON	9.561496	540.396613	24	Gananoque
25	Polygon	Westport	VL	647	364	1.7135	377.5897	ON	2.084239	310.425124	25	Westport
26	Polygon	Rideau Lakes	TP	9687	6568	710.376	13.6364	ON	898.341464	10.783205	26	Rideau Lakes
27	Polygon	Athens	TP	3053	1296	126.4618	24.1417	ON	145.785636	20.941706	27	Athens
28	Polygon	Merrickville-Wolford	VL	2812	1118	213.8128	13.1517	ON	236.925635	11.868703	28	Merrickville-Wolford
29	Polygon	North Grenville	TP	13581	5095	350.1353	38.7879	ON	374.866704	36.228878	29	North Grenville
30	Polygon	Montague	TP	3671	1215	277.0352	13.251	ON	300.003119	12.236539	30	Montague
31	Polygon	Smiths Falls	T	9140	4097	8.2069	1113.697	ON	8.904459	1026.452041	31	Smiths Falls
32	Polygon	Drummond/North Elmsley	TP	6670	3072	364.838	18.2821	ON	418.875688	15.923579	32	Drummond/North Elmsley
33	Polygon	Bathurst Burgess Sherbrooke	TP	5440	3431	527.5835	10.3112	ON	627.549547	8.668638	33	Bathurst Burgess Sherbrooke
34	Polygon	Perth	T	6003	2953	10.3637	579.2333	ON	10.986033	546.421062	34	Perth
35	Polygon	Beckwith	TP	6046	2490	240.1176	25.1793	ON	265.013947	22.813894	35	Beckwith
36	Polygon	Carleton Place	T	9083	3504	8.834	1028.1866	ON	9.639321	942.286319	36	Carleton Place
37	Polygon	Mississippi Mills	T	11647	4383	509.0462	22.88	ON	551.876085	21.104375	37	Mississippi Mills
38	Polygon	Lanark Highlands	TP	4795	2636	1033.3698	4.6402	ON	1144.561659	4.189377	38	Lanark Highlands
39	Polygon	Frontenac Islands	TP	1638	1193	174.9928	9.3604	ON	399.556001	4.09955	39	Frontenac Islands
40	Polygon	Kingston	C	114195	50755	450.3857	253.5493	ON	528.696182	215.993616	40	Kingston
41	Polygon	South Frontenac	TP	16415	8541	941.293	17.4388	ON	1194.661611	13.740293	41	South Frontenac
42	Polygon	Central Frontenac	TP	4557	3378	970.1772	4.6971	ON	1150.244154	3.961768	42	Central Frontenac
43	Polygon	North Frontenac	TP	1801	2739	1135.922	1.5855	ON	1380.417016	1.304678	43	North Frontenac
44	Polygon	Loyalist	TP	14590	5394	340.1478	42.8931	ON	757.381409	19.263742	44	Loyalist
45	Polygon	Greater Napanee	T	15132	6529	459.7066	32.9166	ON	566.698203	26.702043	45	Greater Napanee
46	Polygon	Stone Mills	TP	7337	3120	688.327	10.6592	ON	770.222689	9.525817	46	Stone Mills
47	Polygon	Addington Highlands	TP	2402	2315	1288.8489	1.8637	ON	1478.75792	1.624336	47	Addington Highlands
48	Polygon	Tyendinaga	TP	3769	1330	313.2475	12.032	ON	328.258336	11.48181	48	Tyendinaga
49	Polygon	Deseronto	T	1796	730	2.5192	712.9247	ON	6.778302	264.963095	49	Deseronto
50	Polygon	Tyendinaga Mohawk Territory	R	0	0	69.75	0	ON	91.690742	0	50	Tyendinaga Mohawk Territory
51	Polygon	Belleville	C	45986	20239	241.7936	190.187	ON	272.973986	168.462939	51	Belleville
52	Polygon	Quinte West	C	41409	16946	499.1441	82.96	ON	672.240648	61.598477	52	Quinte West
53	Polygon	Stirling-Rawdon	TP	4887	1893	280.6338	17.4142	ON	294.55851	16.590931	53	Stirling-Rawdon

1 (0 out of 586 Selected)

ON_Mun_Boundary

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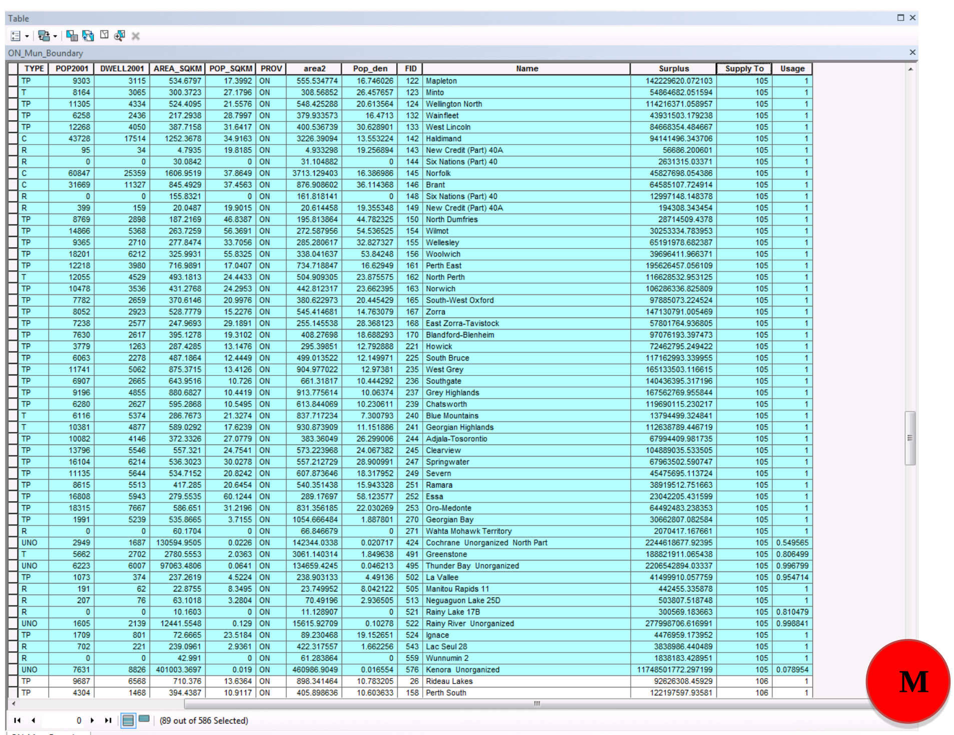
6. Sort the “Supply To” field in the attribute table. And select the rows with “Supply To” FID same with the inquired CSD FID. (i.e. FID-105 for Toronto) (M)



Table

ON_Mun_Boundary

TYPE	POP2001	DWELL2001	AREA_SQKM	POP_SQKM	PROV	area2	Pop_den	FID	Name	Surplus	Supply To	Usage
TP	9303	3115	534.6797	17.3992	ON	555.534774	16.746026	122	Mapleton	142229620.072103	105	1
T	8164	3065	300.3723	27.1796	ON	308.56852	26.457657	123	Minto	54864682.051594	105	1
TP	11305	4334	524.4095	21.5576	ON	548.425288	20.613564	124	Wellington North	114216371.058957	105	1
TP	6258	2436	217.2938	28.7997	ON	379.933573	16.4713	132	Wainfleet	43931503.179238	105	1
TP	12268	4050	387.7158	31.6417	ON	400.536739	30.628901	133	West Lincoln	84668354.484667	105	1
C	43728	17514	1252.3678	34.9163	ON	3226.39094	13.553224	142	Haldimand	94141496.343706	105	1
R	95	34	4.7935	19.8185	ON	4.933298	19.256894	143	New Credit (Part) 40A	56686.200601	105	1
R	0	0	30.0842	0	ON	31.104882	0	144	Six Nations (Part) 40	2631315.03371	105	1
C	60847	25359	1606.9519	37.8649	ON	3713.129403	16.386986	145	Norfolk	45827698.054386	105	1
C	31669	11327	845.4929	37.4563	ON	876.908602	36.114368	146	Brant	64585107.724914	105	1
R	0	0	155.8321	0	ON	161.818141	0	148	Six Nations (Part) 40	12997148.148378	105	1
R	399	159	20.0487	19.9015	ON	20.614458	19.355348	149	New Credit (Part) 40A	194308.343454	105	1
TP	8769	2898	187.2169	46.8387	ON	195.813864	44.782325	150	North Dumfries	28714509.4378	105	1
TP	14866	5368	263.7259	56.3691	ON	272.587956	54.536525	154	Wilmot	30253334.783953	105	1
TP	9365	2710	277.8474	33.7056	ON	285.280617	32.827327	155	Wellesley	65191978.682387	105	1
TP	18201	6212	325.9931	55.8325	ON	338.041637	53.84248	156	Woolwich	39696411.966371	105	1
TP	12218	3980	716.9891	17.0407	ON	734.718847	16.62949	161	Perth East	195626457.056109	105	1
T	12055	4529	493.1813	24.4433	ON	504.909305	23.875575	162	North Perth	116628532.953125	105	1
TP	10478	3536	431.2768	24.2953	ON	442.812317	23.662395	163	Norwich	106286336.825809	105	1
TP	7782	2659	370.6146	20.9976	ON	380.622973	20.445429	165	South-West Oxford	97885073.224524	105	1
TP	8052	2923	528.7779	15.2276	ON	545.414681	14.763079	167	Zorra	147130791.005469	105	1
TP	7238	2577	247.9693	29.1891	ON	255.145538	28.368123	168	East Zorra-Tavistock	57801764.936805	105	1
TP	7630	2617	395.1278	19.3102	ON	408.27698	18.688293	170	Blandford-Blenheim	97076193.397473	105	1
TP	3779	1263	287.4285	13.1476	ON	295.39851	12.792888	221	Howick	72462795.249422	105	1
TP	6063	2278	487.1864	12.4449	ON	499.013522	12.149971	225	South Bruce	117162993.339955	105	1
TP	11741	5062	875.3715	13.4126	ON	904.977022	12.97381	235	West Grey	165133503.116615	105	1
TP	6907	2665	643.9516	10.726	ON	661.31817	10.444292	236	Southgate	140436395.317196	105	1
TP	9196	4855	880.6827	10.4419	ON	913.775614	10.06374	237	Grey Highlands	167562769.955844	105	1
TP	6280	2627	595.2868	10.5495	ON	613.844069	10.230611	239	Chatsworth	119690115.230217	105	1
T	6116	5374	286.7673	21.3274	ON	837.717234	7.300793	240	Blue Mountains	13794499.324841	105	1
T	10381	4877	589.0292	17.6239	ON	930.873909	11.151886	241	Georgian Highlands	112638789.446719	105	1
TP	10082	4146	372.3326	27.0779	ON	383.36049	26.299006	244	Adjala-Tosorontio	67994409.981735	105	1
TP	13796	5546	557.321	24.7541	ON	573.223968	24.067382	245	Clearview	104889035.533505	105	1
TP	16104	6214	536.3023	30.0278	ON	557.212729	28.900991	247	Springwater	67963502.590747	105	1
TP	11135	5644	534.7152	20.8242	ON	607.873646	18.317952	249	Severn	45475695.113724	105	1
TP	8615	5513	417.285	20.6454	ON	540.351438	15.943328	251	Ramara	38919512.751663	105	1
TP	16808	5943	279.5535	60.1244	ON	289.17697	58.123577	252	Essa	23042205.431599	105	1
TP	18315	7667	586.651	31.2196	ON	831.356185	22.030269	253	Oro-Medonte	64492483.238353	105	1
TP	1991	5239	535.8665	3.7155	ON	1054.666484	1.887801	270	Georgian Bay	30662807.082584	105	1
R	0	0	60.1704	0	ON	66.846679	0	271	Wahta Mohawk Territory	2070417.167661	105	1
UNO	2949	1687	130594.9505	0.0226	ON	142344.0338	0.020717	424	Cochrane Unorganized North Part	2244618677.92395	105	0.549565
T	5662	2702	2780.5553	2.0363	ON	3061.140314	1.849638	491	Greenstone	188821911.065438	105	0.806499
UNO	6223	6007	97063.4806	0.0641	ON	134659.4245	0.046213	495	Thunder Bay Unorganized	2206542894.03337	105	0.996799
TP	1073	374	237.2619	4.5224	ON	238.903133	4.49136	502	La Vallee	41499910.057759	105	0.954714
R	191	62	22.8755	8.3495	ON	23.749952	8.042122	505	Manitou Rapids 11	442455.335878	105	1
R	207	76	63.1018	3.2804	ON	70.49196	2.936505	513	Neguaguon Lake 25D	503807.518748	105	1
R	0	0	10.1603	0	ON	11.128907	0	521	Rainy Lake 17B	300569.183663	105	0.810479
UNO	1605	2139	12441.5548	0.129	ON	15615.92709	0.10278	522	Rainy River Unorganized	277998706.616991	105	0.998841
TP	1709	801	72.6665	23.5184	ON	89.230468	19.152651	524	Ignace	4476959.173952	105	1
R	702	221	239.0961	2.9361	ON	422.317557	1.662256	543	Lac Seul 28	3838986.440489	105	1
R	0	0	42.991	0	ON	61.283864	0	559	Wunnumin 2	1838183.428951	105	1
UNO	7631	8826	401003.3697	0.019	ON	460986.9049	0.016554	576	Kenora Unorganized	11748501772.297199	105	0.078954
TP	9687	6568	710.376	13.6364	ON	898.341464	10.783205	26	Rideau Lakes	92626308.45929	106	1
TP	4304	1468	394.4387	10.9117	ON	405.898636	10.603633	158	Perth South	122197597.93581	106	1

0 (89 out of 586 Selected)

ON_Mun_Boundary

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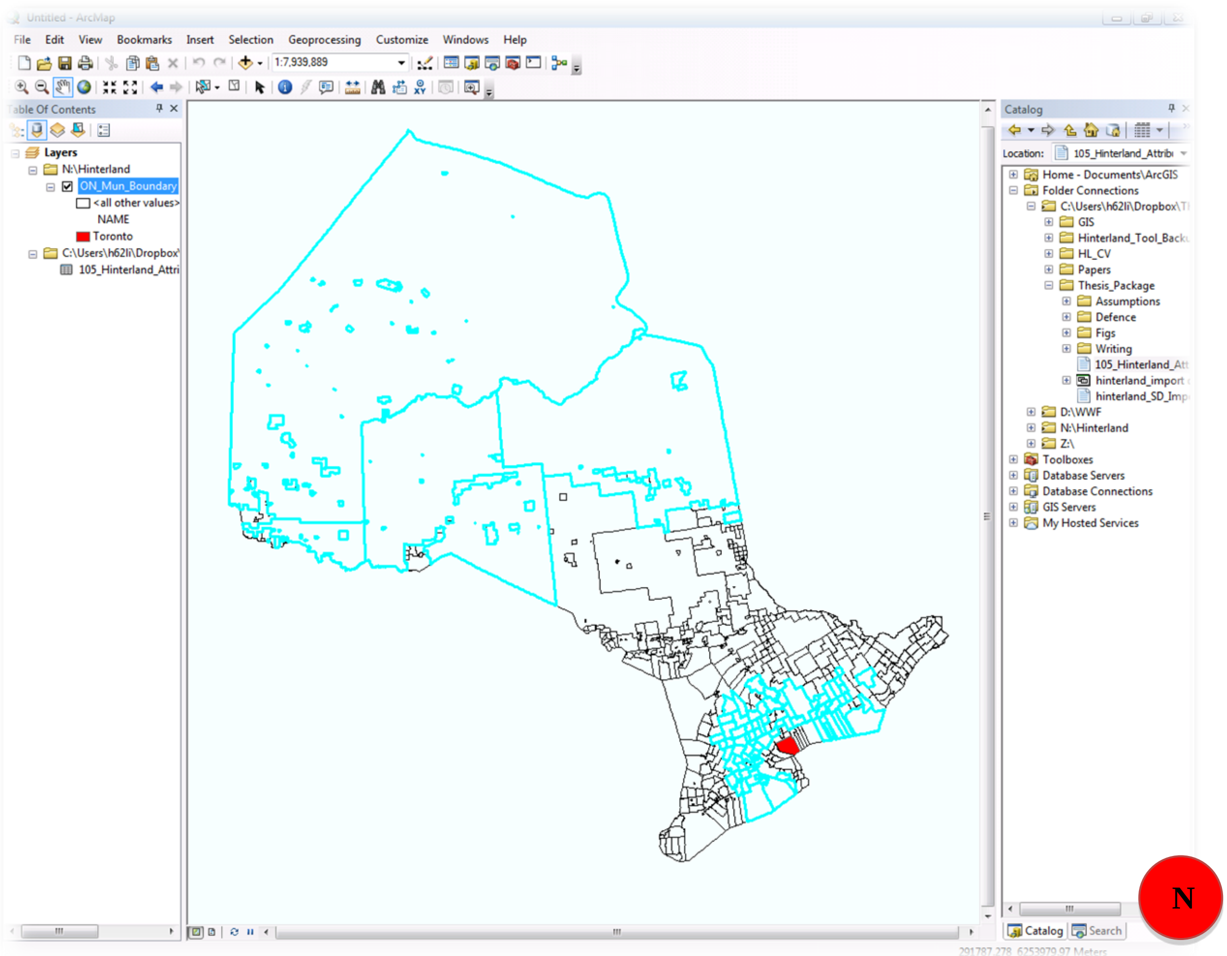
7. (N) is then the electricity supplier map for inquired CSD. (e.g. Electricity Supplier map of Toronto)



8. Export the generated map in different format. And create visualization as pleased.

Appendix VIII: Estimated U.S. Residential Electricity Consumption by End-Use, 2011

End-use	Quadrillion Btu	Billion kilowatthours	Share of total
Space cooling	0.93	273	19%
Lighting	0.63	186	13%
Water heating	0.45	131	9%
Refrigeration	0.38	110	8%
Color televisions and set-top boxes	0.32	93	7%
Space heating	0.27	79	6%
Clothes dryers	0.20	57	4%
Personal computers and related equipment	0.16	46	3%
Furnace fans and boiler circulation pumps	0.13	39	3%
Cooking	0.11	32	2%
Dishwashers[1]	0.10	30	2%
Freezers	0.08	24	2%
Clothes washers[1]	0.03	10	1%
Other uses[2]	1.07	313	22%
Total consumption	4.86	1,424	

[1]Does not include water heating.

[2]Includes small electric devices, heating elements, and motors not listed above.

Source: (U.S. Energy Information Administration, 2013c), Retrieved from
http://www.eia.gov/tools/faqs/faq.cfm?id=96&t=3 on October 15, 2013