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Assessing water use in energy systems: Towards a definition of a water-equivalent footprint (H2Of)

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Assessing water use in energy systems:

Towards a definition of a water-equivalent footprint (H_2O_f)

by

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A THESIS

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Abstract

Efforts to transform energy systems have focused on reducing greenhouse gas (GHG) emissions, yet the energy systems technologies may also have major impacts on water resources. This thesis reports on a meta-analysis of life cycle assessment studies for both GHG emissions and water uses associated with the production of electricity and transportation fuels. The water use of various energy pathways were classified by type and assigned an impact factor (IF) to 'weigh' the environmental cost or benefit of water use assuming regional differences in water availability. This allowed the calculation of a 'water equivalent' footprint (H_2O_f) associated with energy pathways that could be used with CO_2 equivalents (CO_2e) to assess the larger environmental footprint implications of energy systems choices to include both GHG and water use perspectives. With stakeholder input on IF values for a given region, calculations of H_2O_f should provide a useful tool for informing energy systems choices.

Acknowledgements

I cannot express my gratitude enough to my supervisor, Dr. David Layzell. When I first approached him with this project, it was just a few jumbled ideas that I couldn't properly convey. Somehow, he seemed to understand what I meant and offered continual support and encouragement while we figured out just where this project was going to lead. I definitely could not have completed this project without his guidance and this thesis would be much more of a pain to read if he hadn't insisted on continuous logic flow throughout.

I would also like to communicate my sincere gratitude to my committee members, Dr. Joule Bergerson and Dr. Richard Pharis. The feedback and advice offered during committee meetings was invaluable during the creation of this thesis. In addition, the assistance provided outside of the required committee meetings was highly appreciated. I am so grateful that you both went out of your way to assist me during your hectic schedules.

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List of Symbols, Abbreviations and Nomenclature

Symbol/abbreviation/nomenclature	Definition
CCS	Carbon capture and storage is the capture of carbon from a point source and storage in a location where carbon will not enter the atmosphere
CO_2e	Carbon dioxide equivalent is a unit of measurement that described how much carbon dioxide emitted into the atmosphere would cause an equivalent level of radiative forcing as another radiatively active gas by weight
GHG	Greenhouse gas is a gas in the atmosphere that absorbs and emits radiation in the thermal infrared range
LCA	Life cycle assessment is a methodology used to assess the environmental impacts of a product through its life
LHV	Lower heating value represents the net amount of heat energy available to be released by the transformation or use of a specified physical unit of an energy form (does not include the energy used to vaporize water)

Chapter One: **Introduction**

1.1 Statement of the problem

Increasing interest in addressing climate change by focusing on reducing greenhouse gas emissions has prompted a re-evaluation of existing energy systems. In 2009, Canada signed the Copenhagen accord, which states that Canada is committed to reducing GHG emissions to 17% below 2005 levels by 2020 and a 64% reduction by 2050. Currently, approximately 81% of all emissions in Canada are due to the production and use of fossil fuel energy (combination of stationary combustion, transport sources, and fugitive emissions) (Environment Canada 2014). Any reductions made in the energy sector could result in large strides being made toward Canada's Copenhagen target. Unfortunately, many energy* pathways that have the potential to provide GHG reductions utilize large volumes of water or areas of land. Selecting feedstocks for this energy transition by considering climate change benefits alone may result in unintended consequences in the form of water or land use issues.

In many regions of the world, it has become apparent that water demand has exceeded available water supply. Environmental stresses are evident in groundwater depletion, low water flows and the diminishing health of aquatic ecosystems. Demand for freshwater is shared amongst food production, drinking water and increasingly, energy production (Postel 2000). The increased implementation of low water productivity technologies for energy production has the potential to diminish the capacity of the supply to provide for other essential services. In Western Canada, scientists have predicted increased water shortages and decreased water

* In this thesis, 'energy' refers to the production and use of fuels and electricity

quality (Schindler and Donahue 2006). Given the pressures to transform our energy systems, it is important to avoid unintended impacts on water associated with selection of energy feedstocks and conversion technologies.

The volume of water use associated with energy production pathways has been evaluated previously through a variety of proposed methodologies (King and Webber 2008, Hoekstra et al. 2011, Scown et al. 2011). Many of these methodologies focus on the volume of water used, but do not consider the environmental, economic, and social impacts of that water use. In doing so, an incomplete accounting of water use for an energy pathway is formed. This thesis will propose a new methodological approach to evaluate multiple impacts of water use in order to create a holistic depiction of the effects of water use and also add to the research already accomplished on water use for energy production.

1.2 Purpose of the study

The purpose of this thesis was to explore and develop an alternative methodology to account for water use in energy systems. Ideally, the new method will provide a metric that could be used to summarize the large amount of data provided in the literature, incorporate regional human values for water, assist in assessing the costs, benefits and trade-offs of energy systems choices, and ultimately aid in decision making.

1.3 Summary of thesis chapters

Chapter two provides a literature review of the popular methodologies that have been used to account for water use in the production of electricity and transportation fuels. The methodologies can be divided into two types, un-weighted water accounting and weighted water accounting. The former considers only the volume of water used, while the latter attempt to weight water volumes to reflect environmental impacts.

Chapter three introduces the proposed methodology and applies it in a comparative study of feedstocks and pathways for power generation, including both GHG emissions and water use.

Chapter four explores further applications of the proposed methodology. Greenhouse gas emissions and water use are evaluated for transportation fuels. Highlighted in this evaluation are the comparisons between biomass for electricity generation used to support plug-in electric vehicles and biomass for liquid fuel production, i.e. to be blended as E85 and used in an internal combustion engine.

Chapter five is the conclusion of this work, and highlights the beneficial and detrimental aspects of the proposed methodology. In addition, the overall methodological contributions of the study and proposed future research are discussed.

Chapter Two: **Literature Review**

2.1 Introduction

As Canada undergoes a transition from our current energy systems to a new mix of energy feedstocks and conversion technologies, it is important to consider both the intended and unintended costs that may result from these changes in our energy future. There are many factors to consider, including socio-economic, climate change and air quality. However, one factor that is often overlooked involves the use of water in the production of various energy commodities. This is especially pertinent in light of the increasing water scarcity in many areas of the United States and Canada (Schindler and Donahue 2006, "California Approves Hefty Fine for Water-Wasters" 2014, Wines 2014, Nagourney and Lovett 2014).

Although a global water cycle exists, human activity and the production of energy have resulted in the alteration of that cycle. To understand if these changes are sustainable, it is important to be able to account for various types of water and to assess the net cost or benefit of its use. By evaluating feedstocks and pathways of energy production from a water perspective, it may be possible to avoid unintended consequences of the decisions that are made as we transform our energy systems.

Accounting for water use can be highly subjective and many different methods have been proposed. Each methodology presents benefits and drawbacks that we hope to include and avoid within our own methodology.

2.2 Classifications of water and water use

2.2.1 Classification of water

Water was divided by Hoekstra et al. (2011) into three different classifications. Surface and ground water sources were classified as blue water, soil or rainfall water that is not runoff sources were classified as green water, and water that is contaminated during use is known as gray water. With human use or natural processes, water can move between classifications. For instance, blue water can become green water through irrigation or blue and green water can be moved into the atmosphere through evaporation; this water is held as water vapour in the atmosphere until it is returned to blue or green water resources when it falls as precipitation. In this thesis, the classification of water vapour (WV) was added to the previous categories of blue, green and gray water to depict this additional pool within the water cycle (Figure 2.1).

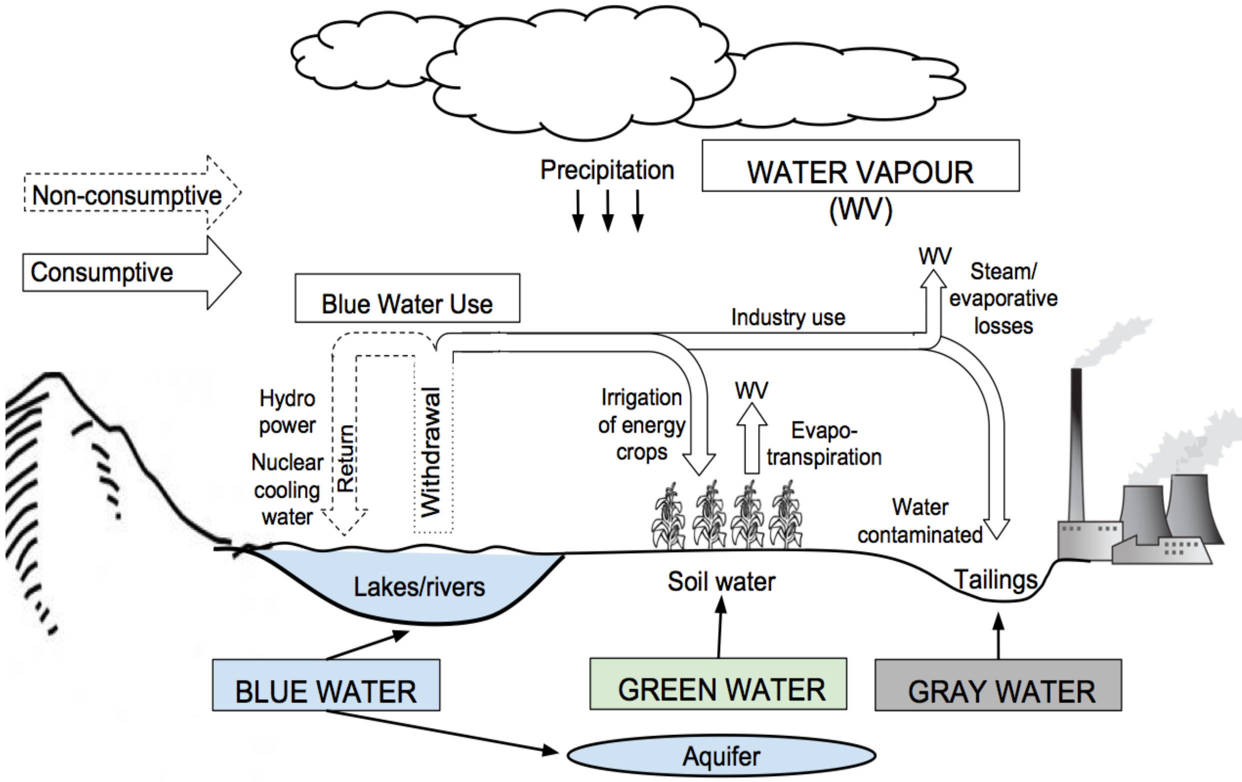

Figure 2.1 Use of blue and green water sources in consumptive and non-consumptive water use for energy production resulting in blue water, green water, gray water, or water vapour

2.2.2 Types of water use

Water withdrawn (used) during the production of energy represents the total volume of freshwater removed temporarily or permanently from a source. The water withdrawn is further divided into two types: water that is never returned to the original source (i.e. water consumption), and water that is returned to the original source (i.e. non-consumptive water use) (Kenny et al. 2009, Kohli et al. 2010) (Figure 2.1).

2.3 Costs and benefits of water use for energy production

Water use may be associated with a myriad of costs and benefits from an environmental, economic and social perspective. Costs of water use for energy production may include negative impacts on fisheries, reduction in water availability for use by cities, industries or food crop production, or adverse impacts of toxins in water on human and animal health. Benefits of water use may include flood or erosion control, or re-establishing the global water cycle that has been impacted by previous human disturbances.

Frequently, only the costs associated with water use have been considered in the literature, but this thesis argues that appreciable benefits of water use do exist. Balancing both the costs and benefits of water use could allow us to determine the best approaches when considering the costs and benefits associated with an energy feedstock and pathway.

2.3.1 Water withdrawal and return (non-consumptive water use)

Many water accounting methodologies disregard non-consumptive water use, but water returned to the original source does not always return unchanged and thus may have a positive or negative effect on the ecosystem.

Water withdrawn and returned to the original source for cooling in thermoelectric power plants may cause negative impacts such as thermal pollution, decreased biodiversity and re-stratification of the water column due to the reduced density of heated water. Conversely, the heated water could be beneficial for the establishment of recreational fisheries as the warmer waters may allow for the introduction of new fish species and increased fishing opportunities in the winter (Olmsted and Bolin 1996) (Table 2.1).

Much of the water utilized in the production of hydroelectricity through large reservoirs remains available for other purposes, which are typically classified as in-stream water use (Kohli et al. 2010). In my thesis water withdrawn and returned through scale large hydro is considered non-consumptive water. Its environmental costs may include adverse impacts on biodiversity (especially fish, other aquatic species, flooded forests) and losses of recreational rivers. On the other hand, potential benefits may include new fishery establishment, flood prevention, security of water supply and lake based recreation (Table 2.1).

2.3.2 Green water consumed as water vapour

The transformation of green water to water vapour via soil and plant evapotranspiration results in an overall depletion of soil water reserves. This is especially important in areas suffering from water scarcity, where crop irrigation is not feasible. In some parts of Canada, 'summer fallow' (fields left with no plants growing for a year) is used to increase soil water reserves and enhance crop growth and yield in the following year (Lindwall and Anderson 1981). Clearly, there is a cost associated with the use of soil water in such regions. However, in regions where water is not the limiting factor, green water that is used for the growth of energy crops may provide positive impacts, such as the prevention of soil erosion and the transfer of water from a non-accessible source to water vapour and thus potentially to a blue water source via rainfall (Table 2.1). Green water as defined herein has limited functional use, as it can only be used by plants and other soil based organisms.

2.3.3 Blue water to green water

Blue water is converted directly to green water through crop irrigation. Although this type of water use is not possible in some regions, for the production of bioenergy crops, irrigation can result in an appreciable increase in yields (McLaughlin and Adams Kszos 2005, Stephen et al. 2010). Unfortunately, irrigation can also have negative impacts. For instance, in many water-limited regions, the salts in soils accumulate in a hardpan zone one meter or so below the soil surface. Irrigation water can solubilise these salts, carrying them to the soil surface, and once this salt laden water evaporates, the soils are rendered unsuitable for agriculture (Pannell and Ewing 2004, Ridley and Pannell 2005). In soils from wetter regions with no hard pan, irrigation can result in ground water pollution if nitrogen and other chemicals in the soil leach into ground water (Table 2.1).

2.3.4 Blue water consumed as water vapour

Blue water has a high initial value due to its flexibility in use; it can be applied to any situation. Due to the high initial value of blue water, the consumptive loss of blue water from a system through water vapour has an increased cost relative to the green water lost from a system. Blue water conversion to water vapour can occur during power generation (thermal or hydro) and incur negative impacts. Water vapour from cooling towers can also mix with pollutants such as sulphur dioxide and nitrogen oxides from the thermoelectric powerplants, eventually yielding an aerosol containing sulphuric acid and nitric acid. Acidic chemicals in the air find their way into the soil through wet deposition and can affect both plants and animals (Likens and Bormann 1974, Likens et al. 1996) (Table 2.1).

Evaporative losses from hydro reservoirs can also transfer blue water into the atmosphere as water vapour, leading to a high water cost. Water lost to the atmosphere increases in hydro reservoirs, relative to the original river, as the reservoirs represent an increased evaporative surface area (Mekonnen and Hoekstra 2011) (Table 2.1).

2.3.5 Blue water contamination

The contamination of water during energy production has no associated positive impacts (Table 2.1). The contaminated water must be treated or diluted, a process that may require additional water use. If treatment is not possible, the result may be permanent or near-permanent removal of this contaminated water from the cycle. Examples are the industrial waters that are deep injected into saline reservoirs, or stored in tailings ponds.

Table 2.1 Examples of water use and their associated negative and positive impacts. Impact factors (IF) attributed to water use have been developed by water weighting approaches.

Water use	Examples	Negative impacts (costs)	Positive impacts (benefits)	Impact factor (IF) given	References
Non-consumptive water use	Water withdrawn and returned for cooling in thermoelectric power plants	• Thermal pollution • Decreased biodiversity • Re-stratification of water column	• Recreational fishery opportunities	0	(Hoekstra et al. 2011)
				0	(Milà i Canals et al. 2009)
				≥ 1	(Pfister et al. 2009)
	Water withdrawn and returned in the production of hydroelectricity	• Decreased biodiversity • Thermal gain	• Potential for new fisheries to occur • Flood prevention • Recreation	0	(Hoekstra et al. 2011)
				0	(Milà i Canals et al. 2009)
				≥ 1	(Pfister et al. 2009)
Green water to water vapour	Green water used in crop growth	• Decrease soil water reserves	• Erosion prevention • Transfer of water in a non-accessible source to another	1	(Hoekstra et al. 2011)
				0	(Milà i Canals et al. 2009)
				Not included	(Pfister et al. 2009)

			classification		
Blue water to green water	Blue water used in crop irrigation	• Soil salinity • Ground water pollution	• Increased agricultural productivity	1	(Hoekstra et al. 2011)
				≥ 1	(Milà i Canals et al. 2009)
				≥ 1	(Pfister et al. 2009)
Blue water to water vapour	Blue water lost to water vapour during power generation	• Acid rain		1	(Hoekstra et al. 2011)
				≥ 1	(Milà i Canals et al. 2009)
				≥ 1	(Pfister et al. 2009)
	Evaporative losses from hydro reservoirs	• Increased losses due to increases in reservoir area and installation of cooling pond installation		1	(Hoekstra et al. 2011)
				≥ 1	(Milà i Canals et al. 2009)
				≥ 1	(Pfister et al. 2009)
Blue water contamination	Water contamination resulting from the production of oil	• Permanent removal of water from all systems or increased		Dilution factor > 1	(Hoekstra et al. 2011)
				Not included	(Milà i Canals et al. 2009)

	and gas	water use required for treatment		≥ 1	(Pfister et al. 2009)

2.4 Weighting water use

Weighted water use methodologies are used to account for the impacts and risks of water use beyond the volume of water; thereby taking into account the differences that may exist in the costs of benefits associated with each type of water use (Table 2.1).

2.4.1 Review of water weighting approaches accomplished with water alone

2.4.1.1 Water footprint

The water footprint is a measure of the volume of direct or indirect freshwater consumption, as well as water contamination (Hoekstra et al. 2011). Non-consumptive water has an effective 'weight' of zero. Water consumption values are first separated into blue, green and gray water classifications. Blue and green water have an inherent weight of one and gray water impact is calculated as the volume of freshwater that is required to assimilate pollutants. Gray water will have a weight that is never less than one.

2.4.1.2 Milà i Canals and colleagues

This method looks at the source and type of water being utilized (Milà i Canals et al. 2009). Blue and green water sources provide water for consumptive or non-consumptive use. Consumptive blue water use is given a weight greater than one. Although green water and non-consumptive water were initially considered, they were later disregarded, as the authors conclude that "green water use leads to no environmental impacts" (Milà i Canals et al. 2009) and that non-evaporative water use does not reflect, from a resources perspective, environmental impacts. Therefore, non-consumptive water use and green water are given an impact factor of zero. Gray water was not included in this methodology.

2.4.1.3 Pfister and colleagues

This approach (Pfister et al. 2009), which considers blue water sources exclusively, includes water use within a watershed. Water use within a watershed is divided into three different categories; non-consumptive water use with an impact factor greater than one as this water use effects water resource availability, consumptive blue water use with an impact factor greater than one; and gray water. Gray water is highlighted as a factor to be assessed in this methodology, but no metric for how to complete this assessment is mentioned. Hence, the associated impact factor is unknown. Green water sources are not included in this methodology.

2.4.2 A review of water weighting based on other environmental impacts

2.4.2.1 Ecopoints

Ecopoints utilize life cycle inventory values from 'cradle to grave' in order to create a composite measure of the environmental impact of a product, material, or service (Dickie and Howard 2000). While typically utilized in evaluating the environmental impacts of building construction (Bartlett and Howard 2000, Vijayan and Kumar 2005), it can also be applied to other processes. For ease of communication and decision-making, this metric reduces 14 impact categories into one ecopoint value. These 14 categories include global warming, photochemical oxidation, ozone layer depletion, eutrophication, human toxicity, land use, freshwater aquatic toxicology, water use, marine aquatic ecotoxicity, terrestrial ecotoxicity, acidification, abiotic depletion, dust, and effects of ionising radiation. Each of these impact categories is evaluated using pre-existing models to calculate their individual environmental impact (ex. CO_2 equivalents). They are then normalised with the total national impact (over a year) caused by an individual. The final values are then weighted using stakeholder-elicited values as to the importance of each category to produce an ecopoint score. As only one of the many impacts considered, water use impact factors are not explicit. In addition, the weighting values vary with each study due to stakeholder engagement.

2.4.2.2 Eco-indicator 99

Eco-indicator 99 is a life cycle impact assessment tool developed by PRé consultants (Goedkoop and Spriensma 2001). It calculates the damage caused by impact factors such as emissions, acidification, and land use on damage categories of human health, ecosystems and resources (Goedkoop and Spriensma 2001). The damage to the above three categories is then consolidated into a single score by the use of weighting factors, which indicate the importance of each damage category as determined by a survey of experts in the field of life cycle assessment (The Ministry of Housing Spatial Planning and the Environment 2000). In this methodology, the weighting factors are pre-set and do not allow for any regional or impact specific distinctions or any positive benefits that could be derived from water use or any other impact considered.

2.5 Conclusion

Understanding the relationship between the production of energy and freshwater use is increasingly important. By evaluating energy pathways from a water perspective it may be possible to provide information as to the overall costs and benefits of water use and highlight potential future concerns. It also allows for the comparison of energy pathways from a perspective additional to the currently established GHG emissions, thereby adding another factor to aid in decision-making.

Chapter Three: **Assessing the water use in power generation, towards enhancing the quantification of a water equivalent footprint (H_2O_f)**

3.1 Introduction

Current energy systems have resulted in a high quality of life, one that many would like to maintain in a more sustainable way. Efforts to transform our energy systems have focused on addressing climate change by reducing greenhouse gas (GHG) emissions. Yet the ultimate selection of technologies for the production and use of energy commodities can have a major impact on both land and water resources. For example, many energy pathways are known to have large demands for water, or they use water in a way that adversely impacts land, biodiversity or other resources (Sovacool 2008, Gerbens-Leenes et al. 2009, Fthenakis and Kim 2010). Therefore, technologies that are able to effectively address GHG emissions (a global issue), that may actually exacerbate local water or land use issues.

Canada is currently in a position to make energy system choices that can have a lasting impact on our future. For example, as of July 2015, Canadian government regulations dictate that when existing coal power plants reach their end of economic life, new power generation infrastructure must meet or exceed emissions intensity of a natural gas, combined cycle facility (defined at 420 t CO_2e/GWh). Due to the age of the existing coal power plants in Canada, these standards will begin affecting units by 2020. Environment Canada predicts that this one regulation will reduce GHG emissions by 3.1 million tonnes below levels projected in 2020, and will do this through changes to both feedstock and conversion technologies (Environment Canada 2013).

To better inform decision-making regarding the implications of energy sources and pathways for power generation, it would be useful to not only assess the GHG footprint (CO_2 equivalents or CO_2e), but also consider other environmental impacts such as water. Numerous studies have assessed the life cycle water use associated with power generation (Berndes 2002, Mielke et al. 2010, Fthenakis and Kim 2010, Wilson et al. 2012) and have concluded that some uses of water, which have much greater environmental impact than others (Hoekstra et al. 2011, Mekonnen and Hoekstra 2011). A simple metric was thus developed to calculate the water footprint of several human activities (including energy systems) as the volume of direct and indirect freshwater consumption and pollution of a product (Hoekstra et al. 2011). In this methodology, non-consumptive water use during energy production has a weight of zero, i.e. no value (Kenny et al. 2009). Water consumption is divided into three separate footprints; blue water (surface/ground water) has an inherent weight of 1; green (soil water) is also given a weight of 1, and gray water (the volume of freshwater that is required to assimilate pollutants) is assigned weight never less than one, as it is dependent on the type of pollutant and the severity of the pollution (Mekonnen and Hoekstra 2010). None of the weighting systems consider the possibility that water use for energy may have a positive impact on the environment, or that it can differentiate between the values assigned to water use in different regions.

The present study explores the feasibility of calculating a 'water equivalent' (H_2O_f) footprint, one where values are given to non-consumptive water uses, and the potential is provided for positive or negative impacts associated with blue and green water. The present study also recognizes regional differences in the values associated with water use. As a case study, it will explore the carbon equivalents (CO_2e) and water equivalent footprints (H_2O_f) associated with a wide range of technologies for producing electrical power by drawing on relevant published results from life cycle assessments (LCAs) of water use, and also of greenhouse gas emissions.

3.2 Materials & Methods

3.2.1 Energy sources and pathways for power generation

A meta-analysis of the published literature and LCAs were utilized to gather data on GHG emissions and freshwater use associated with a variety of different energy pathways that lead to power generation (Figure 3.1). These included coal (with and without carbon capture and storage [CCS]), biomass (residual, and purpose-grown, with and without irrigation), natural gas (conventional and shale gas), large hydro, wind, photovoltaic solar, and uranium. Studies were selected which most closely represented Canadian energy pathways. Or, if Canadian conditions were not unique, values were averaged across a number of studies. Only the use of freshwater was considered in this study; recycled water and salt-water uses were not included.

For each gigajoule of electrical energy generated (GJe), values for the kg of CO_2e emitted, or kg of non-consumptive and consumptive water, were assigned to the appropriate stage in the energy pathway, as shown in Figure 3.1:

- Stage I, resource creation (only relevant for biomass and hydropower production)
- Stage II, recovery, pre-processing and transportation of feedstock;
- Stage III, power generation;
- Stage IV, infrastructure creation, decommissioning and post-generation technologies (e.g. CCS, nuclear waste storage)

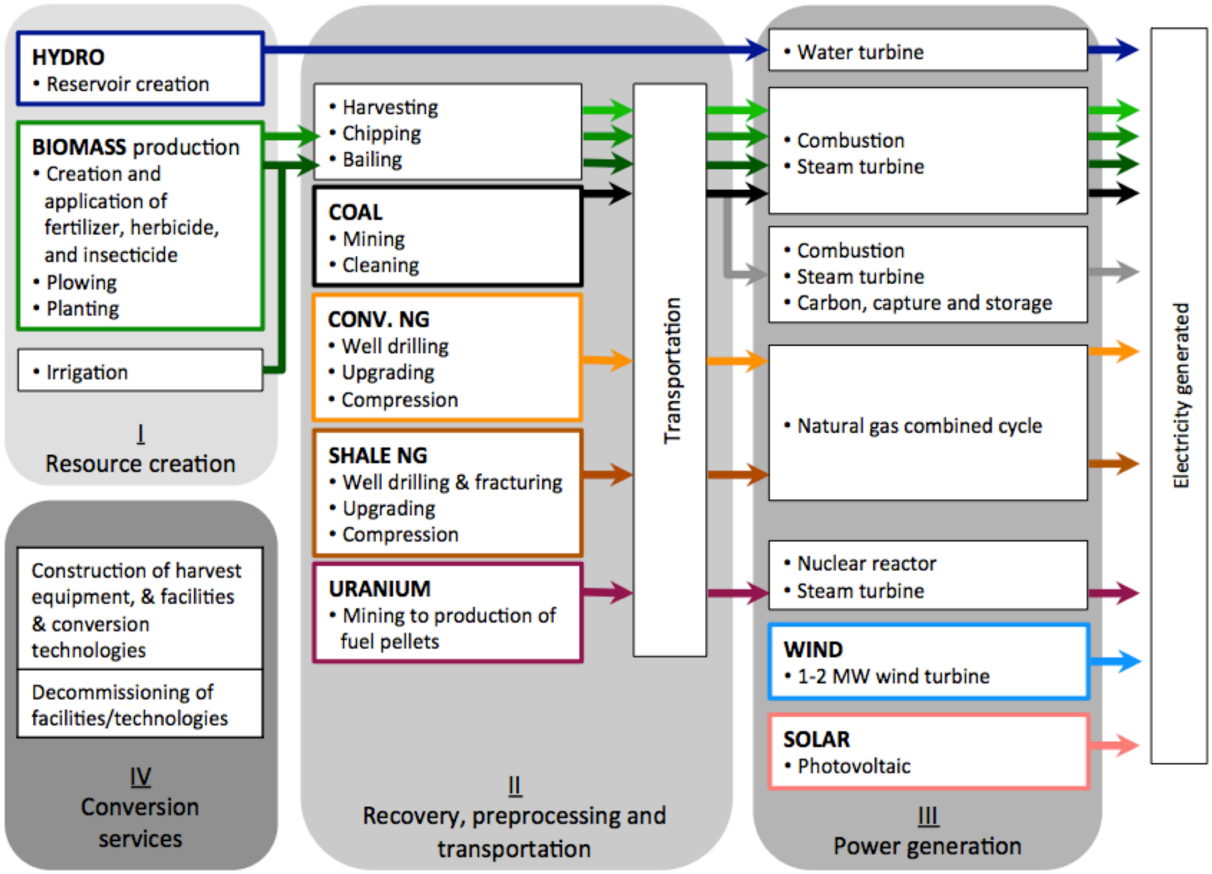

Figure 3.1 The four stages and range of energy sources and conversion processes used in the present study to assess the GHG and water volumes associated with electricity generation.

GHG emissions were assessed in CO_2 equivalents using global warming potentials of 1 for CO_2, 25 for CH_4, and 298 for N_2O over a 100 year time horizon (Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007).

For water use associated with the creation of biomass feedstock, the following equation was used:

$$\frac{kg\ H_2O}{GJe} = \frac{EVT}{HI \times LHV \times CE}$$ Equation 1

where:

EVT is the evapotranspiration rate associated with plant photosynthesis. Values used depended on the plant species and can be found in Appendix A.

HI is the harvest index (units of kg feedstock/kg dry matter). Values used depended on the plant species and can be found in Appendix A.

LHV is the lower heating value for the biomass feedstock and ranges from 16.7 MJ per kg of dry switchgrass (Wu et al. 2006) to 18.6 MJ per kg of dry woody biomass (McKendry 2002). Specific LHV values utilized in each calculation can be found in Appendix A.

CE is the conversion efficiency associated with biomass combustion to drive a steam turbine and is assumed to be 20-40% or 0.2-0.4 GJ electricity (GJe) per GJ thermal (GJt) (McKendry 2002).

3.2.2 Classifying water use

Within each energy pathway and stage, LCA studies were used to allocate water use into five different classifications based on the source of water (blue or green), its ultimate destination (blue, green, gray, and/or water vapour) and the effects of the energy pathway on water quality. My classification scheme (Table 3.1) included the mass of water (in kg) that was removed from blue water and returned to blue water after use (C1), removed from green water and converted to atmospheric water vapour (C2), removed from blue water and converted to green water (C3), removed from blue water and converted to atmospheric water vapour (C4), and removed from blue water and converted to gray water (C5). Examples of each classification type are provided in Table 3.1.

Table 3.1 Classification of freshwater use associated with energy systems pathways and examples of where each use can be found within Canada

Classification (*i*)	**Description [Examples]**
C1	Blue water that returns to blue water after use (i.e. non-consumptive water use) [Majority of hydro and nuclear power generation]
C2	Green water that is converted to atmospheric water/water vapor [Evapotranspiration of biomass crop plants/trees]
C3	Blue water converted to green water [Crop irrigation]
C4	Blue water that is released to the atmosphere as water vapor [Steam lost in thermal power generation, evaporation from hydro reservoir]
C5	Blue water that has been polluted to gray water during use [Oil sands tailing, power plant construction, coal mining]

3.2.3 Assigning impact factors (IF) and calculation of H_2O_f

Associated with each mass of water used within an energy pathway and classification type, an IF was identified to reflect the cost (negative impact) or benefit (positive impact) of water use in one of three (theoretical) regions that differ in their relationship with water:

Scenario region 1 envisages an environment with excessive water and frequent flooding. In such a region there could be benefits from water use, or from infrastructure that might reduce the adverse impacts associated with an excess of water.

Scenario region 2 envisages an environment where there is sufficient water, i.e. it rarely affects demand. In such a region water use would be expected to have a lower cost.

Scenario region 3 envisages a water-constrained environment, one where water limits both socio-economic activity and environmental quality. In such a region, impact factors would be expected to be higher, thereby representing the higher cost of water use.

For each scenario region (R) and energy pathway (P), IF values were generated and used to calculate a water equivalent footprint (${}_{P}^{R}H_2O_f$) using the following equation:

$$ {}_{P}^{R}H_2O_f = \sum_{i=C1}^{i=C5}\left[{}_{P}W_i \times {}_{P}^{R}IF_i \right] \qquad \text{Equation 2}$$

where:

${}_{P}W_i$ is the mass of consumptive or non-consumptive water per GJe generated in classification 'i' in all stages of pathway, P; and

${}_{P}^{R}IF_i$ is the impact factor assigned to water use by classification 'i' in scenario region, R for pathway, P.

An IF value between 0 and 1.0 was considered to be a low cost, whereas an IF > 1.0 was considered to be a relatively high cost. If the water use was determined to have a beneficial impact, the IF was given a negative sign. Therefore, IF values between 0 and -1.0 were considered to be of low benefit and IF values more negative than -1.0 were considered to be strongly beneficial. In the present study, to test the feasibility of this approach, preliminary

${}_{P}^{R}IF_i$ values were assigned based on the author's value assessment for each region (R) and classification of water use (i). More robust values for ${}_{P}^{R}IF_i$ would require the engagement of stakeholders within a given region to assess the value of pertinent water use and to provide a more representative quantitative assessment of the costs or benefits of the various types of water use which are associated with energy systems choices.

3.3 Results

3.3.1 GHG emissions

GHG emissions per GJe generated by 11 different energy pathways representative of those currently in use in Canada are provided in Figure 3.2.

Emissions for the production of electricity from coal were 276 kg CO_2e per GJe (Figure 3.2), with the majority (95%) of the CO_2 emissions being attributed to coal combustion for power generation (stage III) (Zhang et al. 2010). The above values represents one pulverized coal power plant located in Nanticoke, Ontario. Since the Zhang et al (2010) study did not report on the GHG cost of construction and decommissioning (stage IV), these values were estimated as 1% of the total for coal plants in the USA (Meier et al. 2005).

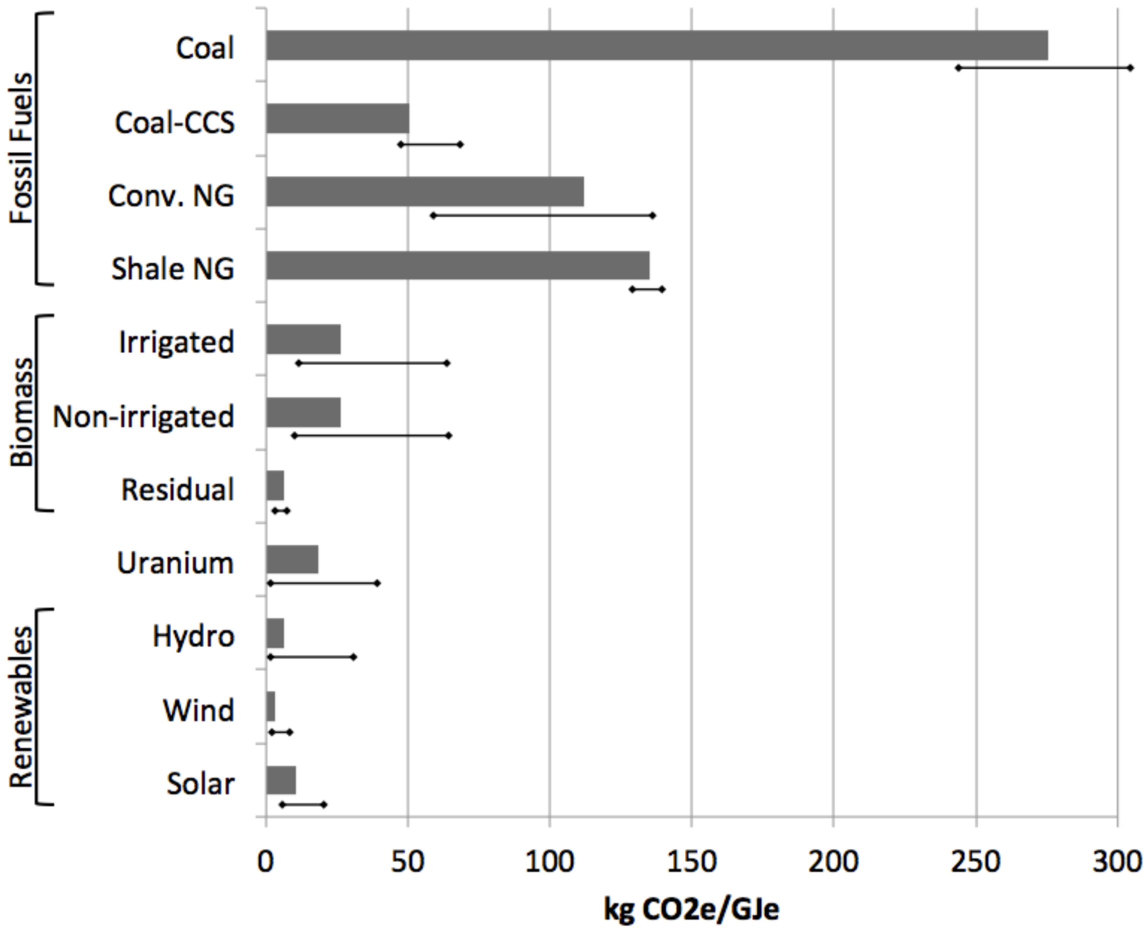

Figure 3.2 Greenhouse gas emissions associated with various generation pathways. The lines below each bar represent the range of values in the literature

The intensity of GHG emissions for coal-CCS plants which use monoethanolamine (MEA) for CO_2 absorption were estimated to be 50.2 kg CO_2e per GJe (Figure 3.2). The recovery, pre-processing and transportation of the coal feedstock (stage II) was estimated to contribute 29% of total emissions while 67% of emissions was attributed to electricity generation in this supercritical pulverized coal power plant with CCS, with CO_2 caputure and geological storage (Zhang et al. 2010). The remaining 4% was associated with the construction and decommissioning (stage IV) of the facility (Meier et al. 2005).

Combined cycle power generation using conventional natural gas was assigned GHG emissions of 112 kg CO_2 per GJe (Figure 3.2), where 14% were attributed to the recovery and pipeline processes (stage II) and 85% to emissions from power generation (stage III) (Zhang et al. 2010). The construction and decommissioning of the gas processing plant and NGCC accounted for less than 1% of total GHG emissions (Meier et al. 2005).

In comparison, combined cycle power generation using shale gas was assigned GHG emissions of 135 kg CO_2e per GJe (Figure 3.2), where 15% of emissions was attributed to stage II (recovery and transportation), with stage III (electricity generation) resulting in 84% of the total emissions (Stephenson et al. 2011, Laurenzi and Jersey 2013). Values for the construction and decommissioning of NG facilities mirror those used in conventional gas and were assumed to represent less than 1% of emissions (Meier et al. 2005).

For the biomass power generation example I used, an irrigated biomass crop as a feedstock to produce first wood pellets, then electricity. The emissions intensity was estimated to be 26 kg CO_2e per GJe (Zhang et al. 2010). Of the total emissions, 82% were produced to harvest, prepare and transport the feedstock (stage II). The biomass pellets and their combustion (stage III) accounted for 17% of all emissions and the creation and decommissioning of the generation facility (stage IV) was estimated at 1% (Zhang et al. 2010).

The study by Sebastian et al. 2007 was used to obtain an estimate of 6.1 kg CO_2e per GJe for emissions associated with converting residual agricultural resides to biomass used for power. The collection and processing of this residue accounted for 26% of the total GHG emissions, power generation for 72%, and 2% for construction and decommissioning.

Uranium mining to pellet formation (stage II) accounted for 36% of the total, 18.4 kg CO_2e per GJe, whereas, 33% was attributed to power generation. Emissions from construction, decommissioning, and spent fuel storage accounted for 31% (Sovacool 2008).

For hydroelectric power, creation of a large hydro reservoir (stage I) was estimated to account for 56% of the total GHG emissions (6.3 kg CO_2e/GJe) (Mallia and Lewis 2012). Typically infrastructure construction costs fall into stage IV, however the reservoir needs to be constructed to create a usable resource, which is why the cost has been allocated to resource creation (stage I). However, the decommissioning costs are still allocated to IV and represent 44% of the total GHG emissions (Mallia and Lewis 2012).

Wind turbine power data was used from on-shore wind farms based in Ontario and assumes a 20-year lifetime of the turbine these are summed as 3.2 kg CO_2e per GJe (Mallia and Lewis 2012). The transportation of wind generators to the site (stage II) accounted for 31% of these emissions while power generation (stage III) represented 6%, and construction and decommissioning (stage IV) accounted for 63% (Mallia and Lewis 2012).

Solar power, GHG emissions were, 10.6 kg CO_2e per GJe (Alsema et al. 2006, Fthenakis and Kim 2007, Weisser 2007), and were associated with the construction of the panels and the upstream resources, balance of system production, and the decommissioning of the panels (stage IV).

3.3.2 Water

Water withdrawal encompasses both consumptive and non-consumptive water use and is provided in Table 3.2 as units of kg H_2O per GJe for all of the various energy pathways. The values presented in Table 3.2 were selected to be representative of electricity generation pathways in Canada.

Table 3.2 Total water use (kg H_2O per GJe) associated with the production of electrical power across stage and classification

Feedstock	Stage	Water use classification	Kg withdrawn water / GJe	References
Coal	II	C1	7.6	(Fthenakis and Kim 2010)
		C5	31.6	
	III	C1	28000	
		C4	580	
	IV	C1	7.8	
	Total		**28600**	
Coal - CCS	II	C1	7.6	(Fthenakis and Kim 2010, Zhai et al. 2011, Wilson et al. 2012)
		C5	31.6	
	III	C1	50400	
		C4	1080	
	IV	C1	7.8	
	Total		**51500**	
Conv. NG	II	C1	19.2	(Fthenakis and Kim 2010, Wilson et al. 2012)
		C5	211	
	III	C1	12100	
		C4	242	
	IV	C1	247	
	Total		**12800**	
Shale NG	II	C1	19.2	(Mielke et al. 2010, Fthenakis and Kim
		C5	219	

	III	C1	12600	2010, Wilson et al. 2012, Nicot and Scanlon 2012, Laurenzi and Jersey 2013)
		C4	242	
	IV	C1	247	
	Total		**13300**	
Bio – dedicated (irrigated)	I	C2	10900	(Koshi et al. 1982, Lindroth et al. 1994, Girouard et al. 1995, Jenkins et al. 1998, Sauerbeck et al. 2001, McKendry 2002, Berndes 2002, McLaughlin and Adams Kszos 2005, Wu et al. 2006, Fthenakis and Kim 2010, Boundy et al. 2011, VanLoocke et al. 2012)
		C3	198000	
	III	C4	500	
	IV	C1	7.8	
	Total		**209000**	
Bio – dedicated (non irrigated)	I	C2	133000	(McKendry 2002, Berndes 2002, Wu et al. 2006, Fthenakis and Kim 2010, Brümmer et al. 2012, VanLoocke et al. 2012)
	III	C4	500	
	IV	C1	7.8	
	Total		**134000**	
Bio – residual	III	C4	500	(Berndes 2002, Fthenakis and Kim
	IV	C1	7.8	

	Total		**508**	2010)
Uranium	II	C1	173	(Fthenakis and Kim 2010, Wilson et al. 2012)
		C5	70.6	
	III	C1	42800	
		C4	282	
	IV	C1	7.4	
		C5	3.2	
	Total		**43300**	
Hydro	III	C1	453000	(Fthenakis and Kim 2010, Wilson et al. 2012)
		C4	9470	
	IV	C5	22.2	
	Total		**463000**	
Wind	IV	C1	66	(Fthenakis and Kim 2010)
		C5	1.1	
	Total		**67**	
Solar	IV	C1	290	(Fthenakis and Kim 2010, Wilson et al. 2012)
		C5	2.1	
	Total		**292**	

3.3.2.1 Coal

Surface mining, processing and transport by rail (stage II) was estimated to withdraw 39 kg H_2O per GJe (Table 3.2), with 7.6 kg H_2O being non-consumptive water use and 31.6 kg H_2O being consumed through contamination during processing. Withdrawal for cooling water during power generation (stage III) was large, but only 580 kg H_2O was lost to the atmosphere as steam, out of the 28,000 kg H_2O withdrawn. This assumes a coal power plant with once-through cooling to mirror the power plant type evaluated for GHG emissions. The water withdrawal associated with the construction and decommissioning (stage IV) of the pulverized coal power plant was 7.8 kg H_2O (Fthenakis and Kim 2010). These values are representative of work in this area and also include water withdrawal values for the decommissioning of the power plant, a value that was left out in many other studies.

3.3.2.2 Coal – CCS

The water volume used for coal with carbon capture and storage (CCS) only differs from coal during power generation (stage III). During this stage, the once-through cooling pulverized coal power plant was utilized for my analysis. Due to the large water withdrawal of once-through cooling, the application of amine-based CCS is not feasible, i.e. direct data is unavailable. Other studies have reported an 82% increase in water use when amine-based CCS is applied to wet tower forced draft coal-fired power plants (Zhai et al. 2011, Wilson et al. 2012). This increase was applied to the values utilized for the coal feedstock (Fthenakis and Kim 2010) and resulted in a withdrawal value of 50,400 kg H_2O per GJe with only 1080 kg H_2O lost to steam (Table 3.2).

3.3.2.3 Conv. NG

Conventional natural gas power from on-shore extraction, preprocessing and transportation (stage II) led to the withdrawal of 230 kg H_2O per GJe. The majority (211 kg H_2O) of this water was consumed due to contamination during extraction. Power generation (stage III) through a natural gas combined cycle (NGCC) with once-through cooling systems, resulted in the withdrawal of 12,400 kg H_2O, most of which was non-consumptive. The remaining 241 kg H_2O was lost to the atmosphere as water vapour (Wilson et al. 2012). During the construction and decommissioning (stage IV) of the NGCC power plant, 247 kg H_2O per GJe were withdrawn (Fthenakis and Kim 2010).

3.3.2.4 Shale NG

Water withdrawal values for the extraction of 'tight' natural gas were not available. Thus, withdrawal values for conventional natural gas were utilized in stage II as the processes overlap except for hydraulic fracturing (Mielke et al. 2010, Nicot and Scanlon 2012, Laurenzi and Jersey 2013). However, the water consumption values associated with hydraulic fracturing were included. The assumption was made that the water consumed during hydraulic fracturing was equivalent to the water withdrawn, as none of the fracturing fluid was returned to the original water source due to contamination. The resulting water withdrawal was 237 kg H_2O per stage II, of which, 219 kg H_2O was contaminated. For power generation and construction and decommissioning (stages III and IV) of a NGCC, the water withdrawals are the same as those used for conventional natural gas as after the recovery of the resource the processes are very similar (Fthenakis and Kim 2010).

3.3.2.5 Bio-dedicated (irrigated)

Water withdrawal during the biomass resource creation (stage I) of irrigated switchgrass and willow was calculated to be 208,900 kg H_2O per GJe (Koshi et al. 1982, Girouard et al. 1995, Jenkins et al. 1998, Sauerbeck et al. 2001, Berndes 2002, McLaughlin and Adams Kszos 2005, Wu et al. 2006, Boundy et al. 2011, VanLoocke et al. 2012). This assumes a power plant efficiency from 20-40% (McKendry 2002), 0.5 to 1.5 kg dry matter of switchgrass shoots per kg water used (VanLoocke et al. 2012), and 3.0 to 3.7 kg dry matter of willow stems per kg water used (Lindroth et al. 1994). Most of the water withdrawn during resource creation was blue water used to irrigate the biomass energy crops, but some of the water was green water transferred to the atmosphere through evapotranspiration. The water withdrawn during power generation (stage III, is considered to be the same for all biomass feedstocks and represents direct combustion in a steam turbine power plan. The water withdrawn for construction and decommissioning (stage IV) of a power plant is considered to be the same across all biomass feedstocks. The water use of stage IV is assigned the same value used in the construction of a steam turbine coal power plant, as the water use is comparable and often the same in coal-biomass co-combustion scenarios (Berndes 2002, Fthenakis and Kim 2010).

3.3.2.6 Bio-dedicated (non-irrigated)

For non-irrigated biomass, the amount of water that is required to create the feedstock (stage I) was calculated to be of 133,000 kg H_2O per GJe and exclusively represents soil water transferred to the atmosphere via evapotranspiration in the production of switchgrass and woody biomass (McKendry 2002, Berndes 2002, Wu et al. 2006, Brümmer et al. 2012, VanLoocke et al. 2012). The water used during stage III and IV is the same as bio-dedicated (irrigated).

3.3.2.7 Bio-residual

The only water use associated with the use of residual biomass is found in power generation (stage III) and the construction and decommissioning of the power plant (stage IV). Use of residual biomass feedstock assumes that any water that went into growth or production is allocated to the primary product.

3.3.2.8 Uranium

Water withdrawal used in uranium mining through to the production of fuel pellets (stage I) was 244 kg H_2O per GJe of which 70.6 kg H_2O were contaminated during mining. For a pressurized water reactor with a once-through cooling, the water withdrawal values are 43,100 kg H_2O per GJe, much of which (42,800 kg H_2O) was returned at an increased temperature to the initial body of water (Fthenakis and Kim 2010, Wilson et al. 2012). Finally, water withdrawal associated with the construction and decommissioning (stage IV) of a nuclear power plant is 11 kg H_2O per GJe (Fthenakis and Kim 2010).

3.3.2.9 Hydro

The water used during hydroelectric power generation is typically classified as in-stream water use rather than water withdrawal, as this water remains in the river or lake (Kohli et al. 2010). In the present study however, we elected to classify this water use as water withdrawal, as there are additional costs associated with this water use outside of water availaibility (Power et al. 1996). A water withdrawal of 463,000 kg H_2O per GJe is associated with power generation, the majority is non-consumptive, but 9470 kg H_2O is lost to the atmosphere (Fthenakis and Kim 2010, Wilson et al. 2012). To construct and decommission a hydroelectric plant (stage IV), 22.2 kg H_2O per GJe was withdrawn (Fthenakis and Kim 2010).

3.3.2.10 Wind

Water withdrawn during the construction of on-shore wind turbines and also in operational cleaning is 67 kg H_2O per GJe. A small portion (1.1 kg H_2O) of this water use is contaminated as a result of wind turbine cleaning (Fthenakis and Kim 2010).

3.3.2.11 Solar

Upstream water withdrawal for the production of photovoltaic panels and maintenance is 292 kg H_2O per GJe (Fthenakis and Kim 2010, Wilson et al. 2012). The majority of this is lost to the atmosphere, but some is contaminated by heavy metals used in panel construction. This value represents an average for two different panel technologies; CdTe and Multi-Si.

3.4 Discussion

3.4.1 GHG emissions in power generation pathways

Expressed per GJe of electricity generated, the life cycle GHG emissions varied among energy pathways by 86 fold (Figure 3.2). From the perspective of lowering greenhouse gas emissions, the best options available are obviously those feedstocks with the lowest GHG emissions (Figure 3.2). In comparison, the more traditional pathways using coal and natural gas (both shale and conventional) have much higher emissions and therefore the lowest on the hierarchy of choosing energy pathways to address climate change.

3.4.2 Water use in power generation pathways

Water withdrawal is the volume of water removed from a source. The water can either be returned to the original source (non-consumptive water use), or consumed (not returned to the source) (Kohli et al. 2010). In the literature, it is water consumption which typically discussed as consumption depicts the water resource availability by expressing that volume of water which is no longer available for use (Harto et al. 2010, Laurenzi and Jersey 2013). However, if the feedstocks are evaluated from the perspective of withdrawal only, the outcome can be very different (Figure 3.3).

Figure 3.3 thus depicts the disparity between consumed and withdrawn water for a particular feedstock. In contrast, most of the literature excludes non-consumptive water use which, in my view is imprudent. This is especially so when there exists evidence that the removal and return process can have a severe impact on local bodies of water. For example withdrawing water from a local source can cause disturbances to the ecological community (Olmsted and Bolin 1996) and disruptions in the flow of water can alter physical habitats, thereby decreasing aquatic biodiversity (Bunn and Arthington 2002). One example is water use for cooling when it is returned to the original source at a higher temperature (Olmsted and Bolin 1996), and action which can have a detrimental effect on aquatic species (U.S. Department of Energy 2006). While it is difficult to value the impacts of withdrawn water, it is evident that there are effects, ones which should be accounted for when comparing the environmental footprint of consumptive and non-consumptive water uses in energy system pathways.

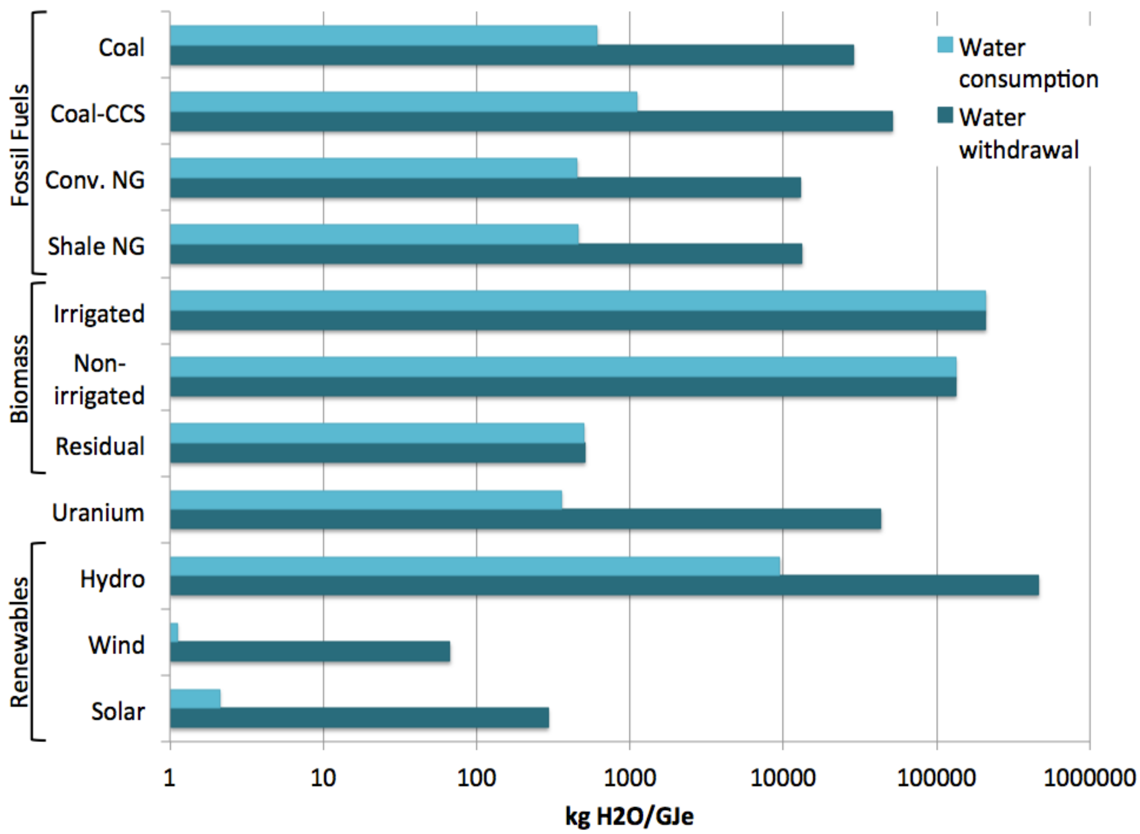

Figure 3.3 Water withdrawal and consumption (kg H_2O/GJe) for power generation on a $\log_{10}$ scale. Non-consumptive water use is represented by the difference between each pair of bars

3.4.3 Evaluation of feedstocks in different scenarios from a water perspective

Water withdrawal is merely a measure of the volume of water used in the production of energy; it gives no indication as to impacts, which may be associated with that water use. To better evaluate impacts, a weighting factor (impact factor) was applied to each consumptive and non-consumptive water use values. These impact factors were determined as a matrix based on two factors; water classification and scenario region.

For water classification effects on impact factors, I assumed that most value systems would place the highest impact (and therefore highest IF) on contaminated water (C5). Additionally, I assumed that non-consumptive water use (C1) would have a very low IF.

The characteristics of a scenario-region will also affect the value of impact factors (Table 3.3). A region subject to frequent flooding, due to high levels of blue water resources and soil saturation is illustrated by scenario region 1. Here, water removal from the system through conversion to water vapour (C2 and C4) is usually beneficial. Also, the magnitude of any water contamination becomes important, as the contamination can become difficult to contain in situations of water excess. The water resources are also high, often exceeding the demand, in scenario region 2, though not to the same extent as scenario region 1. This leads to a decrease in the water IF value and thus a lower water weighting than for scenario 3 (Table 3.3). As water supply is not limited for scenario regions 1 and 2, the primary concern becomes limiting water contamination.

Finally, scenario region 3 represents a region with higher demand than the available water supply. Thus, all water use for scenario region 3 has a cost and the weighting applied is higher than those given to scenarios 1 and 2 (Table 3.3). A more detailed description of how I applied impact factors can be found in Appendix B.

The three scenarios demonstrated how different regions respond to various water situations. The hierarchy of feedstocks will also change when comparing GHG emissions to each water use scenario and across the three scenarios. Such changes in the hierarchy of pathways also change how we make decisions and will increase the complexity of the choice.

Table 3.3 Impact factors for each scenario region

Classification	Scenario region 1	Scenario region 2	Scenario region 3
C1 (non-consumptive)	-0.00005 to +0.0001	+0.0001	+0.0002
C2 (green to WV)	-0.01	0	+0.01
C3 (blue to green)	+0.01	+0.05	+0.1
C4 (blue to WV)	-0.01	+0.1	+1.0
C5 (gray)	+10	+10	+20

3.4.3.1 Coal

In all three scenario regions, coal remains roughly in the middle of the feedstock options (Figure 3.4). In scenario region 1, where coal ranks eighth; the low amount of beneficial water use (C2 or C4) precludes the assignment of a higher rank. In scenario region 2, coal ranks fifth due to the production of contaminated water during the cleaning and processing of coal. Although a premium is also placed on contaminated water in scenario region 3, coal ranks fourth in comparison to alternative feedstocks, due to high levels of overall water use.

3.4.3.2 Coal – CCS

When amine-based carbon capture and storage (CCS) is added to a coal power plant, its efficiency decreases and additional cooling water is required for the carbon capture processes. The increase in cooling water demand leads to higher water withdrawals and thus an overall lower rank for coal with CCS across all scenario regions, when compared to coal without CCS (Figure 3.4).

3.4.3.3 Conv. NG

Although overall water withdrawal is low, natural gas and shale natural gas end up having the highest volume of contaminated water. The IF's in all scenario regions reflect a heavily weighted water contamination. This leads to conventional natural gas being ranked tenth in scenario regions 1 and 2, and ninth in scenario region 3.

3.4.3.4 Shale NG

Shale natural gas is similar to conventional natural gas, but with a slightly higher water contamination level. The increased water contamination leads to shale natural gas being ranked in last place for scenario regions 1 and 2, and tenth place in scenario region 3.

3.4.3.5 Bio – dedicated (irrigated)

Irrigation of crops utilizes a large amount of blue water to create additional green water for crop growth. In addition to the blue water added via irrigation, plants also use pre-existing (green) soil water for growth. Combining these two water sources appreciably increases the water removed from the system and released to the atmosphere via evapotranspiration. Due to this large water use irrigated biomass is ranked first in scenario region 1 when water is in excess. In scenario regions 2 and 3 when there is no longer a benefit (i.e. a negative IF) to water removal from the system, irrigated biomass is a much less viable option, falling to seventh and eighth (Figure 3.4).

3.4.3.6 Bio – dedicated (non-irrigated)

The amount of soil water required for plant growth (C2) is quite large, but is beneficial in scenario region 1 as it removes water from the system, thereby preventing soil saturation. This results in a rank of two (Figure 3.4). For scenario regions 2 and 3, the ranks of non-irrigated biomass fall to fourth and seventh, respectively, as green water conversion to water vapour is no longer considered a net benefit in these scenarios (Figure 3.4).

3.4.3.7 Bio – residual

The water used to produce any residual biomass has previously been allocated to the primary biomass product. Therefore, most water use takes place during power generation, primarily in the loss of cooling water converted to steam. This lower water use, combined with a lack of significant water contamination, results in high rankings across all scenarios; fourth in scenario region 1 and third in scenario regions 2 and 3.

3.4.3.8 Uranium

There are high cooling water demands associated with the use of uranium in nuclear power generating systems and relatively high levels of contaminated water are used per GJe. In scenario regions 1 and 2, uranium ranked ninth and eighth respectively. However it increased to sixth in scenario region 3 due to high non-consumptive water use (Figure 3.4).

3.4.3.9 Hydro

The methodology I used to account for hydro electricity power generation is quite different from the established methodologies in the published literature. Specifically the production of electricity by flowing water via a water turbine. However, water is not 'technically' removed from the system. As such, it is still available for other uses. This is typically classified in the published literature as in-stream water use, and is this excluded from the water withdrawal definition. In my study in-stream water is included in water withdrawal, and this is especially apparent in scenario region one, where water is in excess, i.e. it is ranked third due to the benefits provided in terms of flood control. For scenario regions 2 and 3 hydro electricity power generation is ranked ninth and eleventh, respectively (Figure 3.4). Thus, while the non-consumptive water use (C1) is discounted heavily, it is not enough to account for the large volume of water withdrawn.

3.4.3.10 Wind

The use of wind turbines require the withdrawal of very little water, and their cleaning only results in a small amount of contaminated water. For this reason, wind is ranked number five in scenario region 1 and number one in scenario regions 2 and 3 (Figure 3.4).

3.4.3.11 Solar

Similar to wind, solar utilizes little water. However, it does result in more contaminated water than wind or residual biomass. This puts solar in sixth place after wind for scenario 1 and in second place for scenario regions 2 and 3 (Figure 3.4).

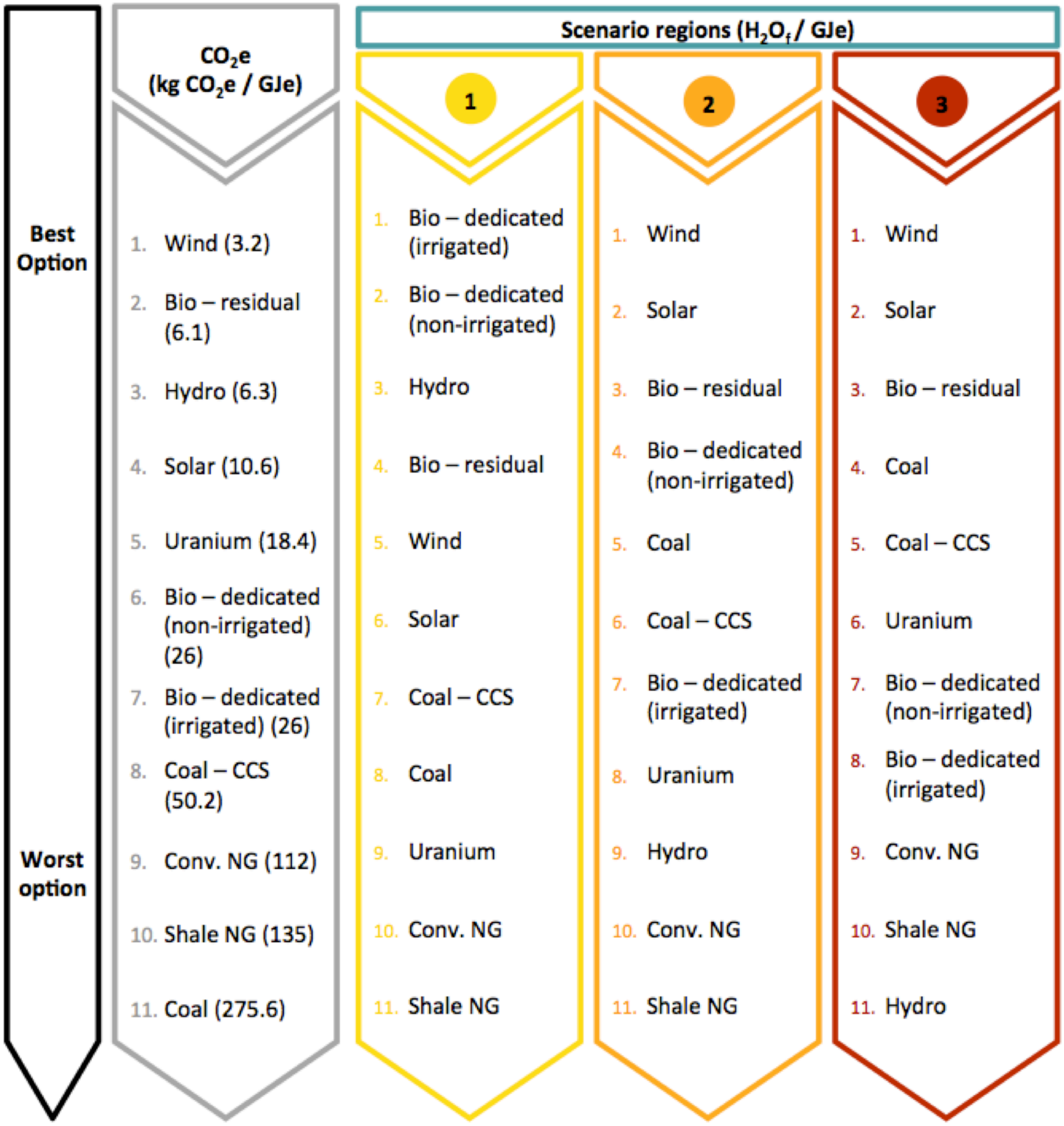

Figure 3.4 Life cycle GHG emissions (kg CO_2e/GJe) and the water use hierarchy of power generation feedstocks, based on scenario region-specific impact factors (see Appendix B)

The impact factors used in this study should be considered as being subjective since a given impact may shift, depending on the region, the technology, and personal opinion. That is the selection of impact factor values for the ranking system was inexact, though I would argue that my relative ranking order would be considered as robust, when assessed by others.

In the future, impact factors should likely be determined on a regional basis (within a community) and should require information and public perception with input from both stakeholders and policy makers. The incorporation of qualitative methodology in conjunction with the assignment of quantitative values, may help to address the current pluralized issues that the environmental weighting factors still face, namely, attempting to describe a qualitative issue in a quantitative manner (Owens 2002).

Chapter Four: **Liquid fuels and biomass comparison**

4.1 Introduction

Concerns about climate change and the production of GHG emissions have increased the interest in transforming existing energy systems. In 2012, 28% of Canada's GHG emissions were associated with transportation (Environment Canada 2014). Energy transitions in the transportation sector could go a long way toward reducing overall emissions.

The need to decrease transportation GHG emissions, in conjunction with high petroleum prices, have led to increased research into the use of biomass feedstocks to provide low carbon sources of renewable energy to support transportation demands (Kheshgi et al. 2000).

Canada, with only 0.5% of the global population (The World Bank - World Development Indicators 2012a), but 7% of global land area (The World Bank - World Development Indicators 2012b), has appreciable biological energy resources. For light duty vehicles (LDVs) used for personal transportation, two main biomass fuel pathways have been proposed as low carbon alternatives. These are the production of ethanol (grain and cellulosic) to be used as a liquid fuel, or electricity generated by biomass, to power electric vehicles.

The ethanol pathway requires the installation of additional infrastructure for fuel production and distribution, but vehicles are now widely available that can utilize a blend of gasoline and ethanol of up to 85% ethanol (E85) (U.S. Depeartment of Energy n.d.). Although the infrastructure exists for the use of electric vehicles, vehicle options are limited, though they are rapidly expanding (Chan 2007).

Biomass use can reduce the amount of GHG emissions produced in supporting transportation demands. However, compared with gasoline, ethanol production from the starch in corn showed only a 21% decrease in GHG emissions. In contrast, cellulose-based ethanol derived from switchgrass shoot tissue showed a 60% reduction in GHG emissions (U.S. Environmental Protection Agency 2010). A similar conclusion was reached when comparing bio-based electricity and electric vehicles against gasoline use in an internal combustion vehicle (Samaras and Meisterling 2008, Hawkins et al. 2013).

Both the production of ethanol and bio-based electricity pathways represent viable, lower carbon alternatives for gasoline. However a comparison between them suggests that electricity from biomass provides the largest GHG reduction (Campbell et al. 2009, Farine et al. 2012). In addition to GHG benefits, utilizing biomass for energy can promote rural economic development (Welling and Shaw 2007), job creation (Best 2012), and economic growth. Since sources are globally distributed they can also enhance energy security for many regions of the world (Bauen 2006), and also create new economic opportunities for generating value from waste.

Although the potential benefits are attractive, one must also look at the costs that such an energy transition may have. What are the associated land use and biodiversity impacts? Does growing bioenergy feedstocks reduce the albedo of sunlight or degrade ecosystems and thereby contribute to climate change? Is there a competition with human food production? And, will a reliance on bioenergy/biofuels contribute to the carbon debt (Jacobson 2009)? There are also a questions on how water resources will be impacted in energy systems that are more dependent on biomass.

The relationship between the growing and use of biomass as an energy resource and the potential impacts on water availability has been a subject of recent debate (Berndes 2002). Recent reports of pending water shortages in western Canada have focused this debate on policy and investment decisions in Canada (Schindler and Donahue 2006).

Previous studies (King and Webber 2008, Scown et al. 2011) have compared the impact of feedstocks for transportation on water use by volume though they did so without acknowledging the value of soil (green) water, or the potential for regional differences in perceived values for water. In my study, a weighting methodology that I developed in the previous chapter (Chapter 3) was used to evaluate the nature and quantity of water use in support of energy use for transportation. The previous chapter explored water use for power generation and in this chapter I will compare water use for differing biomass feedstocks in support of personal transport vehicles. This includes bio-ethanol (from starch or other cellulosic sources) as well as electricity generated from biomass and non-biomass feedstocks.

4.2 Materials & Methods

4.2.1 Energy sources and assumptions for transportation fuels

Information on the GHG emissions and freshwater withdrawal and consumption of an energy pathway was collected from published studies in the literature, with the exception of water used during the resource creation stage (Stage I) of all biomass feedstocks. These stage I values were calculated using Equation 3, which is a slightly altered version of Equation 1 from the previous chapter:

$$\frac{kg\ H_2O}{GJt\ ethanol} = \frac{EVT}{HI \times CE}$$ Equation 3

where:

EVT is the evapotranspiration rate associated with plant photosynthesis (kg H_2O/kg shoots or stems dry matter produced (DM)).

HI is the harvest index (units in kg feedstock/kg DM).

CE is the conversion efficiency associated with biomass conversion to ethanol (L ethanol/kg feedstock)

The lower heating value (LHV) term was removed from this equation, since it no longer applied to the type of conversion factor used for ethanol. For specific values and calculation details, see Appendix A.

The present study considered both liquid transportation fuels and the use of electricity to power a plug-in electric vehicle. The liquid transportation fuels included petroleum (conventional petroleum and oil sands-derived petroleum), compressed natural gas (NG - CNG), corn grain ethanol (irrigated), and cellulosic ethanol from switchgrass (irrigated) or corn stover (residual). The electricity sources included coal, conventional natural gas (NG), biomass crops (irrigated or un-irrigated), and residual biomass.

To compare the various feedstocks and energy system pathways for transportation, values are presented in kg CO_2e per vehicle kilometer travelled (VKT) or kg H_2O per VKT. The values were initially collected as per GJ of energy commodity (gasoline, CNG, ethanol, electricity), but were converted using the following assumptions.

4.2.1.1 Gasoline

A composite litres per 100 kilometers rating for light duty vehicles (LDVs) was calculated. Sixty percent of LDVs are cars, which average 10.5 L per 100 km, and 40% are trucks or SUVs averaging 13.3 L per 100 km. A weighted average of these values results in 11.5 L per 100 km for gasoline LDVs (King and Webber 2008) or 3.68 MJt of gasoline per km travelled (Supple 2007, energy content of gasoline at 32.1 MJt per litre of gasoline).

4.2.1.2 E85

Comparisons of the same vehicles operated with gasoline with E85 displays a 26% decrease in fuel efficiency for a car running on E85 (U.S. Department of Energy 2014). When applied to the 11.5 L per 100 km average used in the gasoline scenario, the new average is 15.5 L per 100 km (King and Webber 2008), or 3.64 MJt of E85 per kilometer travelled (Supple 2007, energy content of ethanol at 21.2 MJt per litre). The energy content of E85 thus resulted in 0.79 MJt ethanol per MJt E85 and 0.21 MJt gasoline per MJt E85.

4.2.1.3 Compressed natural gas (CNG)

I assumed that the fuel efficiency of a natural gas vehicles is the same as gasoline vehicles when 31.9 MJt of natural gas is equal to one L of gasoline, when the energy content of gasoline is 32.1 MJ per L (Supple 2007).

4.2.1.4 Electricity

As for gasoline, the efficiency of electric vehicles was calculated as a composite of the light duty vehicles (LDVs) on the road. Here, LDVs are composed of 30% compact sedans averaging 0.58 MJe per km, 30% are mid-size sedans averaging 0.73 MJe per km, 20% are mid-size trucks/SUVs averaging 0.85 MJe per km, and 20% are full-size trucks/SUVs averaging 1.0 MJe per km (King and Webber 2008). This results in an overall electric vehicle efficiency of 0.76 MJe per km, a value which also accounts for battery and charger efficiency of 87% and 85% respectively. It does not however, include transmission and distribution efficiency of 92% which is applied later (Kintner-Meyer et al. 2007, King and Webber 2008).

4.2.2 Stages in transportation fuel development

After the total freshwater use and GHG emission values were gathered from the literature, portions of the values were assigned to different stages in the supply chain (as described in the previous chapter). The study scope follows the fuel pathway from resource creation to use for transportation, but does not include vehicle production energy or water use costs (Figure 4.1).

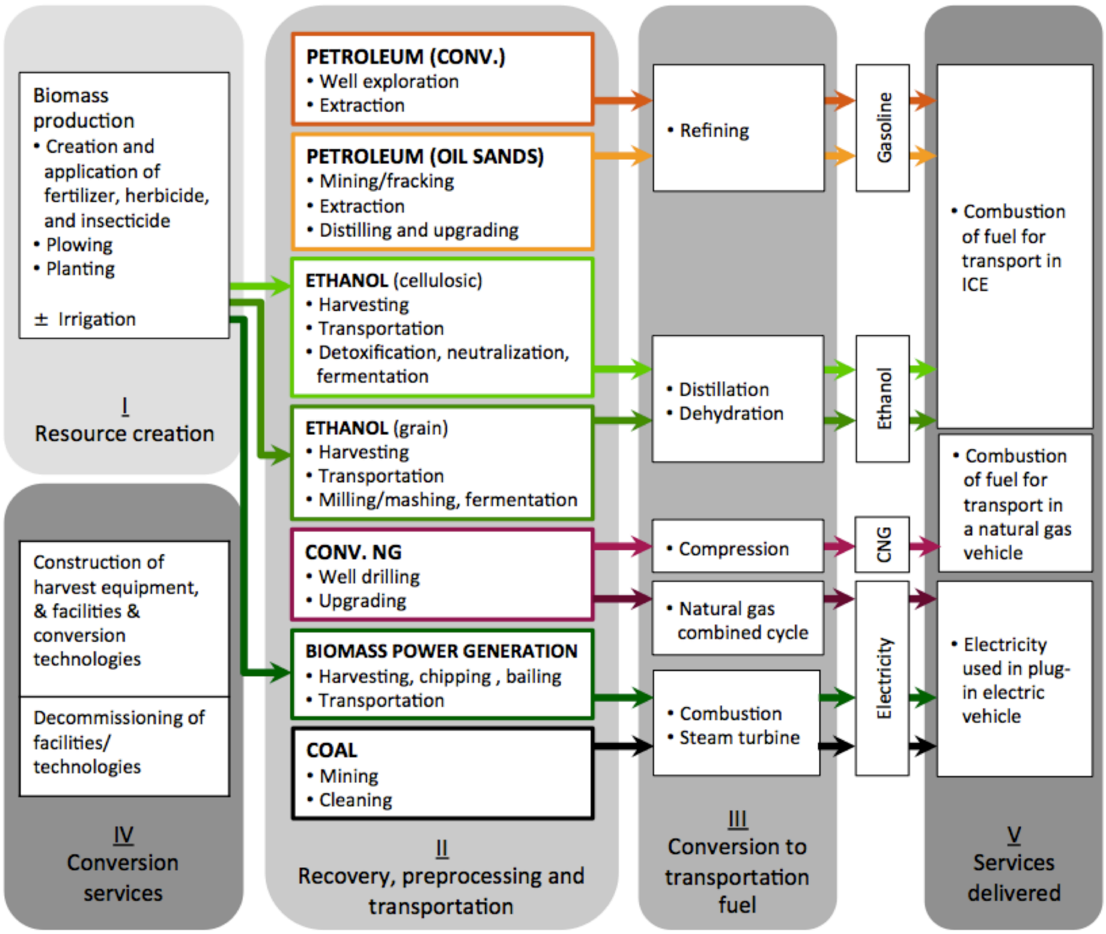

Figure 4.1 Freshwater use and GHG emissions produced in the five stages listed will be discussed. Vehicle production costs are not included in the scope of the project as the values are fairly similar in terms of GHG emissions per vehicle kilometer travelled (Samaras and Meisterling 2008).

Within each stage (Figure 4.1), the water use will be divided into five different classifications based on water pre-use, and on the condition of the water after use (Table 3.1). Each water classification will be assigned an impact factor (IF) based on 'severity' of water use and this IF will be used to calculate the water equivalent footprint (H_2O_f) using Equation 2. The IF can fluctuate depending on regional differences in water availability, as seen in the three example scenarios. In each of these scenarios, the water use availability can vary and thus may cause a shift in the IF and the overall hierarchy of feedstocks in terms of their water use. A more in-depth description of the methodology can be found in the previous chapter.

4.3 Results and Discussion

4.3.1 GHG emissions

The data presented herein represents multiple sources for each feedstock. The sources are selected as they fit within the scope of my analysis and represent a Canadian scenario. For instance, many accounts of switchgrass growth are without irrigation, though within Canada irrigation is frequently used to increase yield. Thus irrigated values are represented within the study, and are identified as such.

The fossil fuel feedstocks assigned to liquid transportation fuels represent the highest GHG emissions per km travelled, due to the amount of emissions released during vehicle use (Figure 4.2). When comparing the various biomass feedstocks to ethanol or electricity, it is apparent that irrigated corn ethanol represents the most GHG-intensive option, whereas use of biomass residues to generate electricity is the least GHG-intensive. Overall, biomass use for transportation produces less GHG emissions than most fossil fuel feedstocks, per km travelled. Although the values are an amalgamation of multiple sources they are similar to GHG emissions published previously (Spatari et al. 2005, Samaras and Meisterling 2008, Campbell et al. 2009, Bergerson et al. 2012, Wang et al. 2012)

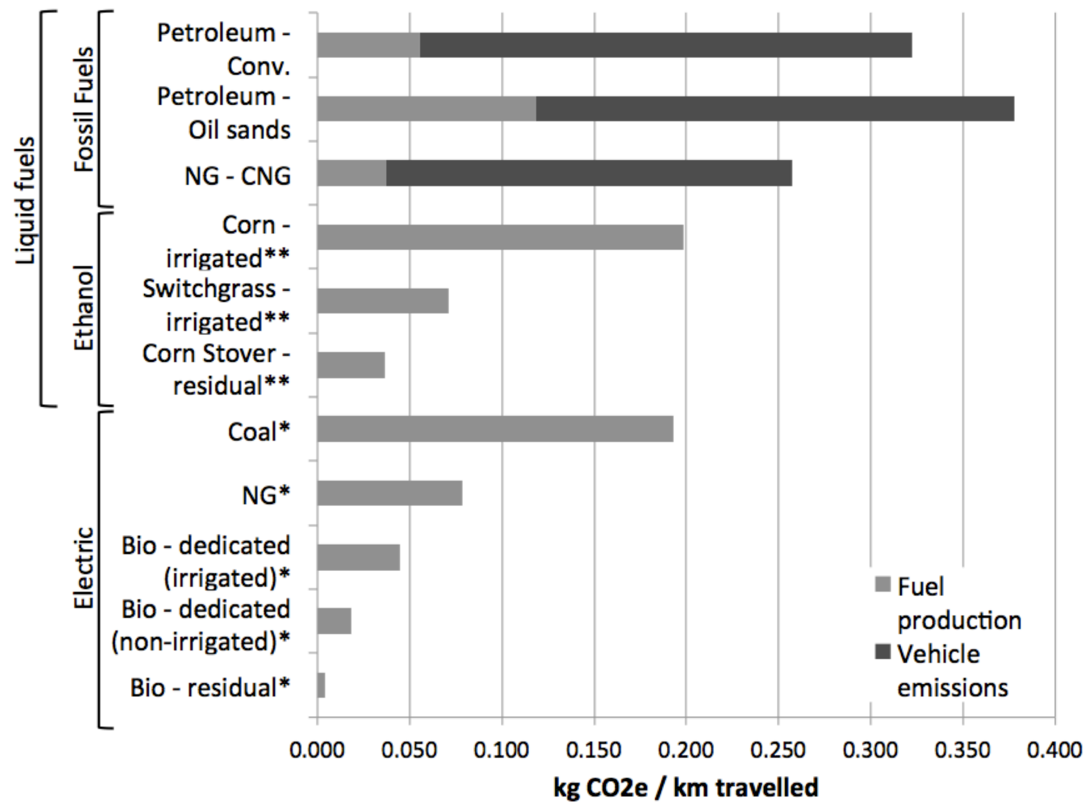

Figure 4.2 GHG (CO_2) emissions released during the production and use of transportation fuels (kg CO_2e per vehicle kilometer travelled [VKT]) for each feedstock.

* Accounts for a total charging efficiency of 68%

** Ethanol here is represented in vehicles as E85 (85% ethanol and 15% gasoline by volume)

4.3.2 Water

4.3.2.1 Un-weighted water use

Unlike the trend observed in GHG emission intensity (Figure 4.2), water use reflects the low water assigned for the fossil fuel feedstocks to be converted to liquid fuels and electricity. In comparison, biomass feedstocks generally have a high water requirement. An exception is the use of biomass residues as a feedstock, e.g. corn stover (Table 4.1).

Biomass conversion to ethanol is more water intensive than biomass conversion to electricity with regard to transportation fuels. Irrigated switchgrass represents the highest water use due to the larger volumes of irrigation water used in the 'resource creation' stage. A similar water use trend exists for irrigated corn. Irrigated and non-irrigated biomass also requires a large amount of water in stage I, though high electric vehicle efficiency reduces the water use impact per km travelled. In contrast, biomass residue feedstocks have very low water use due to the previous allocation, of water used during plant growth, to the primary product.

The fossil fuel to liquid fuel conversion uses much less water than the electricity conversion, unlike biomass feedstocks. This is due to the high amount of water required in cooling steam turbines and natural gas combined cycle power plants. Conventional petroleum represents the lowest water required per km travelled, i.e. 1.6 kg H_2O. The coal to electricity conversion has the highest water use in comparison to other fossil fuel options, 20.1 kg H_2O per km, though it is much lower than the biomass values.

Table 4.1 Un-weighted water use (kg H_2O per vehicle kilometer travelled [VKT]) associated with the production of transportation fuels, across five stages and five classifications

* Accounts for a total battery charging efficiency of 68%

** Ethanol here is represented in vehicles as E85 (85% ethanol and 15% gasoline by volume)

Fuel type	**Stage**	**Classification**	**kg water / VKT**	**Notes and references**
Petroleum – Conv.	II	C5	0.45	Average U.S. crude oil to gasoline values (King and Webber 2008, Scown et al. 2011)
	III	C5	1.1	
	Total		**1.6**	

Petroleum – Oil sands	II	C5	0.53	Average of the low value estimated for surface mining and the high value for in-situ (King and Webber 2008)
	III	C5	1.5	
	Total		**2.03**	
NG – CNG	II	C5	0.10	Conventional natural gas, with natural gas compression (King and Webber 2008)
	III	C5	3.6	
	Total		**3.7**	
Corn – irrigated**	I	C2	286	Stage I, calculated value for water use (Pordesimo et al. 2004, King and Webber 2008, Harto et al. 2010, VanLoocke et al. 2012)
		C3	107	
	II	C1	0.07	
		C5	0.20	
	III	C4	0.80	
	Total		**394**	
Switchgrass – irrigated**	I	C2	462	Stage I, calculated value for water use (Koshi et al. 1982, Sauerbeck et al. 2001, Spatari et al. 2005, Supple 2007, King and Webber 2008, Scown et al. 2011, VanLoocke et al. 2012)
		C3	84	
	II	C1	0.58	
		C5	0.20	
	III	C1	0.32	
		C4	0.50	
	IV	C5	0.01	
	Total		**548**	

Corn stover – residual**	II	C1	0.68	Stage I, calculated value for water use (Pordesimo et al. 2004, Supple 2007, King and Webber 2008, Scown et al. 2011, VanLoocke et al. 2012)
		C5	0.10	
	III	C1	0.04	
		C4	0.80	
	Total		**1.6**	
Coal	II	C1	0.01	Western surface-mined coal, with transport via rail (Fthenakis and Kim 2010)
		C5	0.02	
	III	C1	19.6	
		C4	0.41	
	IV	C1	0.01	
	Total		**20.1**	
NG	II	C1	0.01	On-shore natural gas (NG) extraction followed by electricity generation using a natural gas combined cycle power plant with once through cooling (Fthenakis and Kim 2010, Wilson et al. 2012)
		C5	0.15	
	III	C1	8.5	
		C4	0.17	
	IV	C1	0.17	
	Total		**9**	
Bio – dedicated (irrigated)*	I	C2	138	Stage I, calculated values averaged across multiple biomass feedstocks (switchgrass irrigated, willow) (Koshi et al. 1982, Lindroth et al. 1994, Jenkins et al. 1998, Sauerbeck
		C3	7.6	

	III	C4	0.03	et al. 2001, McKendry 2002, McLaughlin and Adams Kszos 2005, Wu et al. 2006, Fthenakis and Kim 2010, Boundy et al. 2011, VanLoocke et al. 2012)
	IV	C1	0.01	
	Total		**146**	
Bio – dedicated (non-irrigated)*	I	C2	93.1	Stage I, calculated values averaged across multiple biomass feedstock (forest/woody biomass, non irrigated switchgrass) (McKendry 2002, Wu et al. 2006, Fthenakis and Kim 2010, Brümmer et al. 2012, VanLoocke et al. 2012)
	III	C4	0.35	
	IV	C1	0.01	
	Total		**93.5**	
Bio – residual*	III	C4	0.35	(Fthenakis and Kim 2010)
	IV	C1	0.01	
	Total		**0.36**	

4.3.2.2 Weighted water use

The un-weighted freshwater use from Table 4.1 above was evaluated under three different regional scenarios with respect differing water availabilities. Each scenario represents its own challenges, which are reflected in the weighting (see Appendix B). This weighting system was used to allow for a more pertinent discussion beyond just water volumes, as uses of the water can differ appreciably. In addition, regional differences can modify how water is valued, thereby ultimately shifting the hierarchy or feedstocks from a water perspective (Figure 4.3).

4.3.2.2.1 Liquid Fuels

4.3.2.2.1.1 Petroleum – Conv.

The overall water withdrawn during the production of conventional petroleum is very low per VKT, but it does results in contaminated water. Across all scenarios, contaminated water (C5) had an impact of 10 or greater and resulted in a large H_2O_f value and therefore a very low ranking (ninth) across all scenario regions (Figure 4.3).

4.3.2.2.1.2 Petroleum – Oil sands

As for conventional petroleum, the production of petroleum from oil sands contaminates all water used. The high volume of water contaminated per VKT, in conjunction with a high weighting for C5 water, gives a rank of tenth for all scenario regions (Figure 4.3).

4.3.2.2.1.3 NG – CNG

The conversion of natural gas into CNG for use in natural gas vehicles utilizes more water per VKT than either petroleum feedstock, all of which is contaminated during use. Thus, a ranking of last for all scenarios results (Figure 4.3).

4.3.2.2.1.4 Corn – irrigated

In scenario region 1, irrigated corn ethanol was ranked fifth due to the benefits attributed to green water converted to water vapour through evapotranspiration. In scenario regions 2 and 3 where high water use is less beneficial, the water required for plant growth increased the overall H_2O_f of the pathway. Therefore, the rank of irrigated corn decreased to eighth in scenario regions 2 and 3 (Figure 4.3).

4.3.2.2.1.5 Switchgrass – irrigated

Ranked first in scenario region one, irrigated switchgrass provides benefits to a waterlogged system through evapotranspiration during growth and during the loss of blue water to evapotranspiration during ethanol production (Figure 4.3). This combined with low contamination gave a negative H_2O_f value, one that denotes that the positive impacts of water use outweighs the negative impacts.

Similar to irrigated corn for grain ethanol, once water use was no longer considered beneficial, the rank of irrigated switchgrass decreased to seventh in scenario regions 2 and 3.

4.3.2.2.1.6 Corn stover – residual

As corn stover is a residual feedstock there is no water input associated with resource creation, as water use is allocated to the primary biomass product. Though water withdrawal is low, contamination of water prevented a higher (better) rank for the corn stover pathway. Across all scenarios regions, corn stover is ranked fifth (Figure 4.3).

4.3.2.2.2 Electricity

4.3.2.2.2.1 Coal

Thermoelectric power generation causes an increase of water withdrawal for cooling. When compared against traditional transportation fuels such as petroleum, the un-weighted water use is 20-fold higher (Table 4.1). Despite this water use disparity, coal ranks above all other fossil fuel pathways for liquid fuels across all scenario regions (Figure 4.3). This is due to the low level of water contamination throughout the pathway, and also the small IF values applied to non-consumptive water use (C1) across all scenario regions.

4.3.2.2.2.2 NG

Natural gas use for electricity generation ranked eighth in scenario region 1 and sixth in scenario regions 2 and 3. Natural gas did rank higher than the two other petroleum fossil fuel pathways for liquid fuels across all scenario regions (Figure 4.3).

4.3.2.2.2.3 Bio – dedicated (irrigated)

Like all biomass feedstocks, the water utilized in resource creation is very large. In scenario region 1, this large water use is beneficial and gives a negative overall H_2O_f value and a high rank of second. In scenarios 2 and 3 the rank falls to fourth (Figure 4.3).

4.3.2.2.2.4 Bio – dedicated (non-irrigated)

Non-irrigated biomass ranked third in scenario region 1, second in scenario region 2, and third in scenario region 3. The relatively high rankings are due to the absence of irrigated water during the growth phase of the feedstock and no water contamination (Figure 4.3).

4.3.2.2.2.5 Bio – residual

Residual biomass is ranked fourth in scenario region 1 and first in scenario regions 2 and 3 (Figure 4.3). Residual biomass for power generation fares better than residual biomass (corn stover) used for ethanol production due to the lack of water contamination and also, in part, to the increased efficiency of an electric vehicle, when compared to an internal combustion engine (ICE) running on E85.

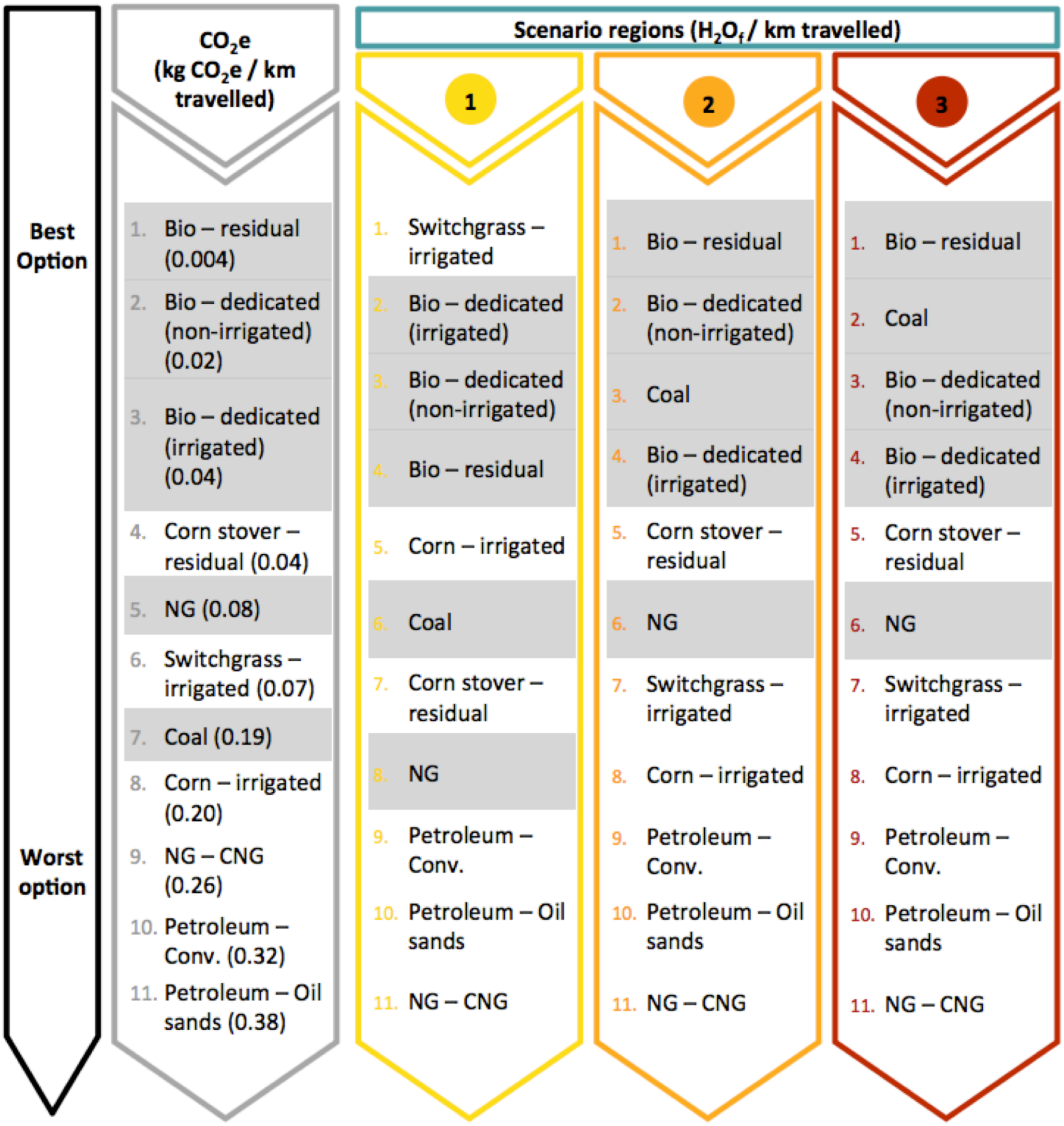

Figure 4.3 Life cycle GHG emissions (kg CO_2e/vehicle kilometer travelled [VKT]) and water use hierarchy of feedstocks based on scenario region-specific impact factors (see Appendix B). Feedstocks shaded gray represent electricity generation technologies.

Chapter Five: **Conclusion**

5.1 The water equivalent footprint methodology

The water footprint methodology proposed here draws on a vast amount of data available on freshwater use, transforming it into an impact factor (IF). If I have been successful, these impact factors can be use to further our understanding of water use impacts, make comparisons among energy pathways, and inform policy investment decisions. In essence, it recognizes that different uses for water have different costs or benefits, and that these can vary with region and personal priorities/value systems.

Water use of a feedstock was first divided into the stages in the life cycle of energy production, from creation of the energy feedstock, through recovery, preprocessing and transport, to conversion to a commodity and use. Then it was classified by the type of water use, a procedure which takes into account the status of water before and after use. The breakdown of water use by type is notable, as it allowed for the capacity to assign impacts to specific types of water use. The impacts were then weighted and water values were aggregated for each energy feedstock to give a single value, the water equivalent footprint (H_2O_f). It is this value, which represents the environmental, economic and social impacts of water use.

The application of the IF to classified water uses relative allows a differentiated weighting to be given, for example, to contaminated water relative to the environmental effects of non-consumptive water use, or to soil water used for crop growth. All of these water uses are very different and represent their own impacts and challenges. Additionally, unlike much of the literature, the methodology described in this thesis includes water withdrawal values and also recognizes green water as a source with value.

In chapters three and four, the water equivalent footprint methodology was applied to water use of feedstocks used for electricity generation and for the production of transportation fuels. The feedstocks were evaluated in three scenario regions, each of which represents regions of varying water availability. Due to the differences in water availability, the impacts of different types of water were found to vary among scenario regions. An across-scenario comparison demonstrates just how much feedstocks shift in favourability when societal priorities and perspectives change. This demonstrates the necessity of region-based impact factors, as there is no universal set of values that can express the concerns of all regions accurately.

Within any one regional scenario, my methodology puts feedstocks on a basis of equal comparison. When comparing water volume use alone, many important factors remain. By separating and weighting water use by type, one can reflect issues such as contamination or habitat loss. Within any one region, where all the impact factors are applied, the rankings can be used as a decision-making tool. The consolidation of water use impacts into a single value also allows for comparison across energy feedstocks, thereby enabling that value to be used together with other decision-making factors such as CO_2e.

5.2 Limitations

Limitations of my study include:

1. The use of a meta-analysis to summarize and integrate results from multiple studies may introduce a publication bias, or the over-representation of work that has been published (Walker et al. 2008). In my study, several unpublished research papers; such

as student theses and gray literature were included. However, the majority of my data was collected from the published literature.

2. Studies included in the meta-analysis were selected based on their objectives, the outcomes measured, and my view of the quality of data. While this was done to reduce the variables introduced, it may present some selection bias on my part.
3. It is possible that my methodology may over-simplify the various impacts of water use. Although the use of water represents a single input, the use of water can result in a variety of impacts such as habitat quality, low oxygen content, or loss of biodiversity. My water equivalent footprint combines these variable issues into a set of impact factors. The combination of multiple impacts, where important impacts become one of many, increases the need to establish transparency in data collection and methodology. The classification of water use and the classification specific impact factors were developed primarily as a method to calculate an H_2O_f value in order to add detail that is sometimes lost in the interest of obtaining an easily comparable value.
4. My methodology was limited by the water use values available in the literature. For emerging and controversial technologies, locating reliable water use data with adequate detail was difficult. As the water use values were divided by stage and then classification, significant detail with regards to data collection and sources was necessary for use. The values utilized in chapters two and three were carefully constructed from hundreds of sources to accurately depict water use of a feedstock. The

data collection for this methodology was thus time consuming, but did allow for increased detail in the analysis.

5.3 Methodological contributions

My methodology is reminiscent of multiple water accounting methods. Much of the terminology such as blue, green and gray water was defined in the water footprint methodology put forward by Hoekstra et al. (2011). Also, the division of water use by stage is a common practice in life cycle assessments. By utilizing previous research and established water accounting methods to inform and structure my water equivalent footprint, it was possible to address some of the shortcomings noted in the literature.

My methodology attempted to include all freshwater use in the analysis, specifically non-consumptive water use (C1 water) and green water, which often had not been included in previous methodologies. My inclusion of consumptive water use thus drastically changed the values expressed in chapters three and four, relative to literature values. This was especially apparent in water use values associated with hydroelectric power generation and for water use values of biomass feedstocks, and the overall outcome in the ranking of these feedstocks.

I also tracked water use values from inputs to the status of water post-use. This tracking was included in my classification system and allows water to be traced from blue and green sources to blue, green, water vapour (atmospheric water), and then to gray water after use. This inclusion of detail was important, as it gives an impression of the water value both prior to and after use. For instance, blue water is valuable, as it has the potential to be used for many purposes; the conversion of blue water to gray water constitutes a reduction in the water value. Gray water signifies the water removal from the system and needs to be treated before future use. Although, blue water conversion to water vapour yields a reduction in value, the reduction is not as large as conversion of blue to gray water due to the fact that water vapour can result in rainfall, and thus result in available water in another region, water which does not need any additional treatment.

Finally, the water equivalent footprint methodology utilizes scenario or regional specific impact factors, ones which address more than water scarcity issues. The impact factors are intended to convey the need to consider multiple impacts, and how those impacts interact with any regional factors.

5.4 Future work recommendations

In the future, to further understand the water cost of biomass, it may be helpful to compare native vegetation water use and crop water use. The difference would reflect the human impact on the water cycle and the specific cost of biomass-based energy. The assumption being that the land that will be used to grow biomass crops would otherwise be filled with native vegetation, and thus still consume soil water via evapotranspiration.

Further research needs to be completed on the development of my impact factors utilized in the 'water equivalent footprint methodology'. Determination of impact factors through qualitative methodology can identify what to focus on for a specific region; i.e. it can help to identify what is important. This is especially important as water use leads to many diverse impacts. There can be readily quantifiable impacts such as eco-toxicity and water scarcity, to cultural beliefs tied to water, ecosystem health and habitat quality, the latter being hard to characterize numerically. Impact factors determined by stakeholder opinion can reflect regional issues and potentially give a feedstock or pathway social license to practice. This can also be applied directly to decision-making. By establishing what trade-offs a region or community is willing to make, and what their highest priority is, it should become easier to focus decision-making.

The engagement through surveys and interviews of stakeholders, such as academics, investors, and members of the community, can yield information on which community perception of water use can be based. This would allow a more informed application of water weighting factors to power generation and production of transportation fuels. It would also then be possible to assess:

a. How these opinions and viewpoints can be incorporated into the 'water equivalent' footprint methodology
b. How a different perspective can change the importance of various water factors
c. If participants are presented with the results of their weighting choice, is there a change in their responses?
d. How the responses of stakeholder groups may differ from those provided by the general public
e. How stakeholder and public perception might affect water use management strategies

5.5 Significance of the study

This study may prove significant in contributing to the area of research related to water use in power generation and liquid fuels production. The meta-analysis conducted can provide detailed water use information on multiple feedstocks and can act as an available database of values. The main significance of this study lies in the creation of a novel methodology that can be used to evaluate water use and the corresponding impacts. The methodology promotes the inclusion of additional water inputs and the evaluation of multiple impacts of water use. Research of this kind is significant to stakeholders in the community and policy makers. Understanding the implications of energy decisions on water use can aide in future decision making and policy creation. In addition, this methodology can expand beyond the applications demonstrated in this thesis such as the determination of water impacts associated with a product or processes outside of energy production. In a more general sense, the methodological framework and inclusion of qualitative methodology can be applied to concerns other than water, for instance land use impacts.

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Appendix A: **CALCULATIONS OF WATER USE IN BIOMASS RESOURCE CREATION**

The calculation of water withdrawal in biomass resource creation is similar for all types of biomass. Equation 1 was used to calculate the mass of water (kg) that is required to create enough biomass to produce one GJ of commodity (either electricity or transportation fuels).

$$\frac{kg\ H_2O}{GJe} = \frac{EVT}{HI \times LHV \times CE}$$

where:

EVT is the evapotranspiration rate associated with plant photosynthesis (kg H_2O/kg dry matter (DM)).

HI is the harvest index (units of kg feedstock/kg dry matter).

LHV is the lower heating value for the biomass feedstock (MJ (t or e)/kg dry matter).

CE is the conversion efficiency.

If ranges of values were present in the literature, the maximum and minimum options were calculated from which an average was taken to produce an overall value for the feedstock.

Electricity Generation

Overall powerplant efficiency for the direct combustion of biomass to generate electricity ranged from 20%-40% (McKendry 2002).

Biomass (irrigated)

Calculated the water withdrawal that is required for the creation of switchgrass and willow biomass. These two plants were selected as they align with the NRCAN report for biomass feedstocks of interest in Canada (Natural Resources Canada 2012). The values for switchgrass and willow were averaged to produce an overall value for irrigated biomass.

Switchgrass

EVT = 10^4 kg H_2O/5-15 kg DM switchgrass (VanLoocke et al. 2012)

HI = 1 kg feedstock/1kg DM as all aboveground biomass is harvested for use

LHV = 16.7 MJ/kg DM (Wu et al. 2006)

Additional conversion factors:

GJ = 1000 MJ

Using the low end range of values (10^4 kg H_2O/5kg DM and 20% efficiency)

=[(10^4 kg H_2O/5 kg DM) / (1 kg feedstock/1 kg DM) / (16.7 MJ/kg DM) / (0.2 GJe/GJt)] * (1000 MJ/GJ)

=598800 kg H_2O/GJe

Using the high end range of values (10^4 kg H_2O/15 kg DM and 40% efficiency)

=[(10^4 kg H_2O/15 kg DM) / (1 kg feedstock/1 kg DM) / (16.7 MJ/kg DM) / (0.4 GJe/GJt)] * (1000 MJ/GJ)

=99800 kg H_2O/GJe

Willow

EVT = 1 kg H_2O/3.0-3.7 g above ground dry matter (Lindroth et al. 1994)

HI = 1 kg feedstock/1kg dry matter as all aboveground biomass is harvested for use

LHV = 16.7-18.4 MJ/kg dry matter (Jenkins et al. 1998, Boundy et al. 2011)

Additional conversion factors:

GJ = 1000 MJ

Kg = 1000 g

Using the low end range of values (1kg H_2O/3 grams above-ground DM, 16.7 MJ/kg DM and 20% CE)

=[(1kg H_2O/3 g DM) / (1 kg feedstock/kg DM) / (16.7 MJ/kg DM) / (0.2 GJe/GJt)] * (1000 MJ/GJ) * (1000 g/kg)

=99800 kg H_2O/GJe

Using the high end range of values (1 kg H_2O/3.7 grams above ground DM, 18.4 MG/kg DM and 40% CE)

=[(1kg H_2O/3.7 g DM) / (1 kg feedstock/kg DM) / (18.4 MJ/kg DM) / (0.4 GJe/GJt)] * (1000 MJ/GJ) * (1000 g/kg)

=36720 kg H_2O/GJe

Value used for dedicated biomass (irrigated)

=(598800 + 99800 + 99800 + 36720)/4

=**208800 kg H_2O/GJe**

Dedicated biomass (non-irrigated)

Biomass (non-irrigated) values are comprised of switchgrass, willow coniferous boreal and temperate forests, and coastal forest. These biomass types were selected as they align with the NRCAN report for biomass feedstocks of interest in Canada (Natural Resources Canada 2012). The values of all biomass types were averaged to produce an overall value for biomass (non-irrigated).

Switchgrass

EVT = 10^4 kg H_2O/5-15 kg DM switchgrass (VanLoocke et al. 2012)

HI = 1 kg feedstock/1kg DM as all aboveground biomass is harvested for use

LHV = 16.7 MJ/kg DM (Wu et al. 2006)

Additional conversion factors:

GJ = 1000 MJ

Using the low end range of values (10^4 kg H_2O/5kg DM and 20% efficiency)

=[(10^4 kg H_2O/5 kg DM) / (1 kg feedstock/1 kg DM) / (16.7 MJ/kg DM) / (0.2 GJe/GJt)] * (1000 MJ/GJ)

=598800 kg H_2O/Gje

Using the high end range of values (10^4 kg H_2O/15 kg DM and 40% efficiency)

=[(10^4 kg H_2O/15 kg DM) / (1 kg feedstock/1 kg DM) / (16.7 MJ/kg DM) / (0.4 GJe/GJt)] * (1000 MJ/GJ)

=99800 kg H_2O/GJe

Coniferous boreal and temperate forests

EVT = 1000 kg H_2O/5.81-7.17 kg DM woody biomass (Brümmer et al. 2012)

Note: Values from Brümmer et al. were given as grams C and converted to biomass using a ratio of 51.6% C in woody biomass (McKendry 2002).

HI = 1 kg feedstock/1 kg DM as all above ground biomass is harvested

LHV = 18.6 MJ/kg DM (McKendry 2002)

Addition conversion factors:

GJ = 1000 MJ

Using the low end range of values (1000 kg H_2O/5.81 kg DM and 20% CE)

=[(1000 kg H_2O/5.81 kg DM) / (18.6 MJ/kg DM) / (0.2 GJe/GJt)] * (1000 MJ/GJ)

=46270 kg H_2O/GJe

Using the high end range of values (1000 kg H_2O/7.17 kg DM and 40% CE)

=[(1000 kg H_2O/7.17 kg DM) / (18.6 MJ/kg DM) / (0.4 GJe/GJt)] * (1000 MJ/GJ)

=18750 kg H_2O/GJe

Coastal forest

EVT = 1000 kg H_2O/11.6 kg dry woody biomass (Brümmer et al. 2012)

Note: Values from Brümmer et al. were given as grams C and converted to biomass using a ratio of 51.6% C in woody biomass (McKendry 2002).

HI = 1 kg feedstock/1kg DM as all above ground biomass is harvested

LHV = 18.6 MJ/kg DM (McKendry 2002)

Additional conversion factors:

GJ = 1000 MJ

Using the low end range of values (20% CE)

=[(1000 kg H_2O/11.6 kg DM) / (1 kg feedstock/kg DM) / (18.6 MJ/kg DM) / (0.2 GJe/GJt)] * (1000 MJ/GJ)

=23170 kg H_2O/GJe

Using the high end range of values (40% CE)

=[(1000 kg H_2O/11.6 kg DM) / (1 kg feedstock/kg DM) / (18.6 MJ/kg DM) / (0.4 GJe/GJt)] * (1000 MJ/GJ)

=11590 kg H_2O/GJe

Value used for dedicated biomass (non-irrigated)

=(598802 + 99800 + 46270 + 18750 + 23170 + 11590)/6

=**133100 kg H_2O/GJe**

Transportation Fuels

For the calculation of water use during boimass creation per GJt of ethanol, the formula is similar to that of Equation 1 for power generation.

$$\frac{kg\ H_2O}{GJ\ ethanol} = \frac{EVT}{HI \times CE}$$

where:

EVT is the evapotranspiration rate associated with plant photosynthesis (kg H_2O/kg dry matter (DM)).

HI is the harvest index (units of kg feedstock/kg DM).

CE is the conversion efficiency associated with biomass conversion to ethanol (L ethanol/kg feedstock)

The LHV is removed from this equation, as it no longer applied to the type of conversion factor used for ethanol.

Corn – irrigated

EVT = 555.6 kg H_2O/kg above ground DM corn grain (VanLoocke et al. 2012)

HI = 0.46 kg corn grain/kg DM (Pordesimo et al. 2004)

CE = 0.42 L ethanol/kg corn grain (King and Webber 2008)

Note: Value given as gallons ethanol per bushed and converted using 56 lb corn grain/bushel (Pordesimo et al. 2004), 2.2 lb/kg, and 0.264 gallon/liter (Supple 2007)

Additional conversion factors:

Liter ethanol = 21.2 MJ (Supple 2007)

GJ = 1000 MJ

Total water use for the creation of corn grain

=[(555.6 kg H_2O/kg DM) / (0.46 kg Corn grain/kg DM) / (0.42 L ethanol/kg Corn grain) * (1 L ethanol/21.2 MJ) * (1000 MJ/GJ)

=**136600 kg H_2O/GJ ethanol**

Switchgrass – irrigated

EVT = 666.7-2000 kg H_2O/kg DM switchgrass (VanLoocke et al. 2012)

HI = 1 kg feedstock/1 kg DM as all above ground biomass is harvested

CE = 0.33 L ethanol/kg DM switchgrass (Spatari et al. 2005)

Note: Initially given as L ethanol/megagram DM switchgrass and converted using Megagram = 1000 kg

Additional conversion factors:

Liter ethanol = 21.2 MJ

GJ = 1000MJ

Using the low yield scenario (2000 kg H_2O/kg DM switchgrass)

=[(2000 kg H_2O/kg DM switchgrass) / (1 kg feedstock/1 kg DM) / (0.33 L ethanol/kg DM switchgrass)] * (1 L ethanol/21.2 MJ) * (1000 MJ/GJ)

=285900 kg H_2O/GJ ethanol

Using the high yield scenario (666.7 kg H_2O/kg DM switchgrass)

=[(666.7 kg H_2O/kg DM switchgrass) / (1 kg feedstock/1 kg DM) / (0.33 L ethanol/kg DM switchgrass)] * (1 L ethanol/21.2 MJ) * (1000 MJ/GJ)

=95290 kg H_2O/GJ ethanol

Total water use for the creation of switchgrass

=(285900 + 95290)/2

=**190600 kg H_2O/GJ ethanol**

Appendix B: **WATER IMPACT FACTORS**

Impact factors for scenario region 1

The region represented in scenario 1 has water in excess and experiences problems with flooding. Non-consumptive water use (C1) is discounted heavily in this scenario (IF is less than one (Table B.1)), but it is still not zero because of the need to account for additional environmental impacts. Water removed from the system for C2 (green to WV) and C4 (blue to WV) represents a benefit to the scenario region 1 system as it reduces the water load in the region and aids in prevention of soil saturation and flooding. The benefit to the system was thus denoted with a negative IF value of -0.01. Water moved from blue to green (C3) is not as beneficial as C2 and C4 water as the water is moved only within the same system and has a IF of +0.01 (Table B.1). Finally, contaminated water (C5) has a large impact in this scenario. With an increased amount of water use, contaminated water can become extremely difficult to contain and may affect surrounding land or other water bodies. In my study all of the C5 IF values initially began with a dilution of 10, which was then scaled up based on the conditions associated with scenario region 1. Thus in scenario region 1, the IF associated with C5 water use is 10, multiplied by a scaling factor of one (Table B.1).

Impact factors for scenario region 2

In scenario region 2, the volume of water use is less important than in scenario region 3, as the freshwater supply in the region exceeds water demand. Water use in scenario region 2 thus represents no benefit and therefore all IF values are greater than or equal to zero. Non-consumptive water (C1) remains available for use, so while the value is not zero (due to other environmental impacts), the IF is less than 1.0, i.e. it is acting as a discount factor for the non-consumptive water use. For classifications of C2, C3 and C4 water, the IF values were determined based on comparisons with scenario regions 1 and 3. Contaminated water, C5, was assigned an IF of 10, and was multiplied by a scaling factor of one.

<u>Impact factors for scenario region 3</u>

Scenario region 3 represents a region with an insufficient supply of water to meet demand. Therefore, all water is valuable and all types of water use have an associated cost (IF greater than zero). Non-consumptive water, C1, is assigned an impact factor of +0.0002. This is a steep discount awarded because, the water remains available for future use. C2 water represents green water that is moved to the atmosphere as water vapour. In scenario region 3, C2 and C4 water uses were considered to have the same overall effect, water removal from the system. However, blue water has a higher initial value, and thus resulted in a slightly higher IF for C4 when compared to C2. The conversion of blue water to green water (C3) during crop irrigation is an unlikely occurrence in a highly water stressed region. However, it is included for completeness. Finally, the contamination of water during use (C5) is given the highest weight. It thus either needs to be treated before future use, which typically required more water input, or it can never be used again. For scenario region 3, the impact of C5 water is represented by an IF of 20, the dilution factor scaled by a factor of 2.

Table B.1 Impact factors associated with classification for water use across three different scenario regions

Classification	Scenario region 1	Scenario region 2	Scenario region 3

C1 (non-consumptive)	-0.00005 to +0.0001	+0.0001	+0.0002
C2 (green to WV)	-0.01	0	+0.01
C3 (blue to green)	+0.01	+0.05	+0.1
C4 (blue to WV)	-0.01	+0.1	+1.0
C5 (gray)	+10	+10	+20

Table B.2 Impact factors applied to the water use associated with electricity generation for three scenario regions

Feedstock	Stage	Water use classification	Kg withdrawn water / GJe	Scenario 1 (H_2O_f)	Scenario 2 (H_2O_f)	Scenario 3 (H_2O_f)
Coal	II	C1	7.6	0.00076	0.00076	0.00152
		C5	31.6	316	316	632
	III	C1	28000	2.8	2.8	5.6
		C4	580	-5.8	58	580
	IV	C1	7.8	0.00078	0.00078	0.00156
	Total		**28600**	**313**	**377**	**1220**
Coal - CCS	II	C1	7.6	0.00076	0.00076	0.00152
		C5	31.6	316	316	632
	III	C1	50400	5.04	5.04	10.08
		C4	1080	-10.8	108	1080
	IV	C1	7.8	0.00078	0.00078	0.00156

	Total		**51500**	**310**	**429**	**1720**
Conv. NG	II	C1	19.2	0.00192	0.00192	0.00384
		C5	211	2110	2110	4220
	III	C1	12100	1.21	1.21	2.42
		C4	242	-2.42	24.2	242
	IV	C1	247	0.0247	0.0247	0.0494
	Total		**12800**	**2110**	**2140**	**4460**
Shale NG	II	C1	19.2	0.00192	0.00192	0.00384
		C5	219	2190	2190	4380
	III	C1	12600	1.26	1.26	2.52
		C4	242	-2.42	24.2	242
	IV	C1	247	0.0247	0.0247	0.0494
	Total		**13300**	**2190**	**2220**	**4610**
Bio – dedicated (irrigated)	I	C2	198000	-1980	0	1980
		C3	10900	109	545	1090
	III	C4	500	-5	50	500
	IV	C1	7.8	0.00078	0.00078	0.00156
	Total		**209000**	**-1880**	**595**	**3570**
Bio – dedicated (non irrigated)	I	C2	133000	-1330	0	1330
	III	C4	500	-5	50	500
	IV	C1	7.8	0.00078	0.00078	0.00156

	Total		**134000**	**-1340**	**50**	**1830**
Bio – residual	III	C4	500	-5	50	500
	IV	C1	7.8	0.00078	0.00078	0.00156
	Total		**508**	**-5**	**50**	**500**
Uranium	II	C1	173	0.0173	0.0173	0.0346
		C5	70.6	706	706	1412
	III	C1	42800	4.28	4.28	8.56
		C4	282	-2.82	28.2	282
	IV	C1	7.4	0.00074	0.00074	0.00148
		C5	3.2	32	32	64
	Total		**43300**	**726**	**770**	**1770**
Hydro	III	C1	453000	-22.7	45.3	90.6
		C4	9470	-94.7	947	9470
	IV	C1	22.2	-0.0011	0.0022	0.0044
	Total		**463000**	**-117**	**992**	**9560**
Wind	IV	C1	66	0.0066	0.0066	0.0132
		C5	1.1	11	11	22
	Total		**67**	**11**	**11**	**22**
Solar	IV	C1	290	0.029	0.029	0.058
		C5	2.1	21	21	42
	Total		**292**	**21**	**21**	**42.1**

Table B.3 Impact factors applied to the water use associated with transportation fuel and electricity generation for use it transportation for three different scenario regions

* Accounts for a total charging efficiency of 68%

** Ethanol here is represented in vehicles as E85 (85% ethanol and 15% gasoline by volume)

Fuel type	Stage	Classification	Kg water / VKT	Scenario 1 (H_2O_f)	Scenario 2 (H_2O_f)	Scenario 3 (H_2O_f)
Petroleum – Conv.	II	C5	0.45	4.5	4.5	9
	III	C5	1.1	11	11	22
	Total		**1.6**	**15.5**	**15.5**	**31**
Petroleum – Oil sands	II	C5	0.53	5.3	5.3	10.6
	III	C5	1.5	15	15	30
	Total		**2.03**	**20.3**	**20.3**	**40.6**
NG – CNG	II	C5	0.10	1.0	1.0	2.0
	III	C5	3.6	36	36	72
	Total		**3.7**	**37**	**37**	**74**
Corn – irrigated**	I	C2	286	-2.86	0	2.86
		C3	107	1.07	5.35	10.7
	II	C1	0.07	0.000007	0.000007	0.000014

		C5	0.20	2	2	4
	III	C4	0.80	-0.008	0.08	0.8
	Total		**394**	**0.202**	**7.43**	**18.4**
Switchgrass – irrigated**	I	C2	462	-4.62	0	4.62
		C3	84	0.84	4.2	8.4
	II	C1	0.58	0.000058	0.000058	0.000116
		C5	0.20	2	2	4
	III	C1	0.32	0.000032	0.000032	0.000064
		C4	0.50	-0.005	0.05	0.5
	IV	C5	0.01	0.1	0.1	0.2
	Total		**548**	**-1.68**	**6.35**	**17.7**
Corn stover – residual**	II	C1	0.68	0.000068	0.000068	0.000136
		C5	0.10	1	1	2
	III	C1	0.04	0.000004	0.000004	0.000008
		C4	0.80	-0.008	0.08	0.8
	Total		**1.6**	**0.993**	**1.08**	**2.8**
Coal	II	C1	0.01	0.000001	0.000001	0.000002
		C5	0.02	0.2	0.2	0.4
	III	C1	19.6	0.00196	0.00196	0.00392
		C4	0.41	-0.0041	0.041	0.41
	IV	C1	0.01	0.000001	0.000001	0.000001

	Total		**20.1**	**0.202**	**0.243**	**0.814**
NG	II	C1	0.01	0.000001	0.00001	0.000002
		C5	0.15	1.5	1.5	3
	III	C1	8.5	0.00085	0.00085	0.0017
		C4	0.17	-0.0017	0.017	0.17
	IV	C1	0.17	0.000017	0.000017	0.000034
	Total		**9**	**1.50**	**1.52**	**3.17**
Bio – dedicated (irrigated)*	I	C2	138	-1.380	0	1.38
		C3	7.6	0.076	0.38	0.76
	III	C4	0.03	-0.0003	0.003	0.03
	IV	C1	0.01	0.000001	0.000001	0.000002
	Total		**146**	**-1.30**	**0.383**	**2.17**
Bio – dedicated (non-irrigated)*	I	C2	93.1	-0.931	0	0.931
	III	C4	0.35	-0.0035	0.035	0.35

	IV	C1	0.01	0.000001	0.000001	0.000002
	Total		**93.5**	**-0.934**	**0.035**	**1.28**
Bio – residual*	III	C4	0.35	-0.0035	0.035	0.35
	IV	C1	0.01	0.000001	0.000001	0.000002
	Total		**0.36**	**-0.0035**	**0.035**	**0.35**