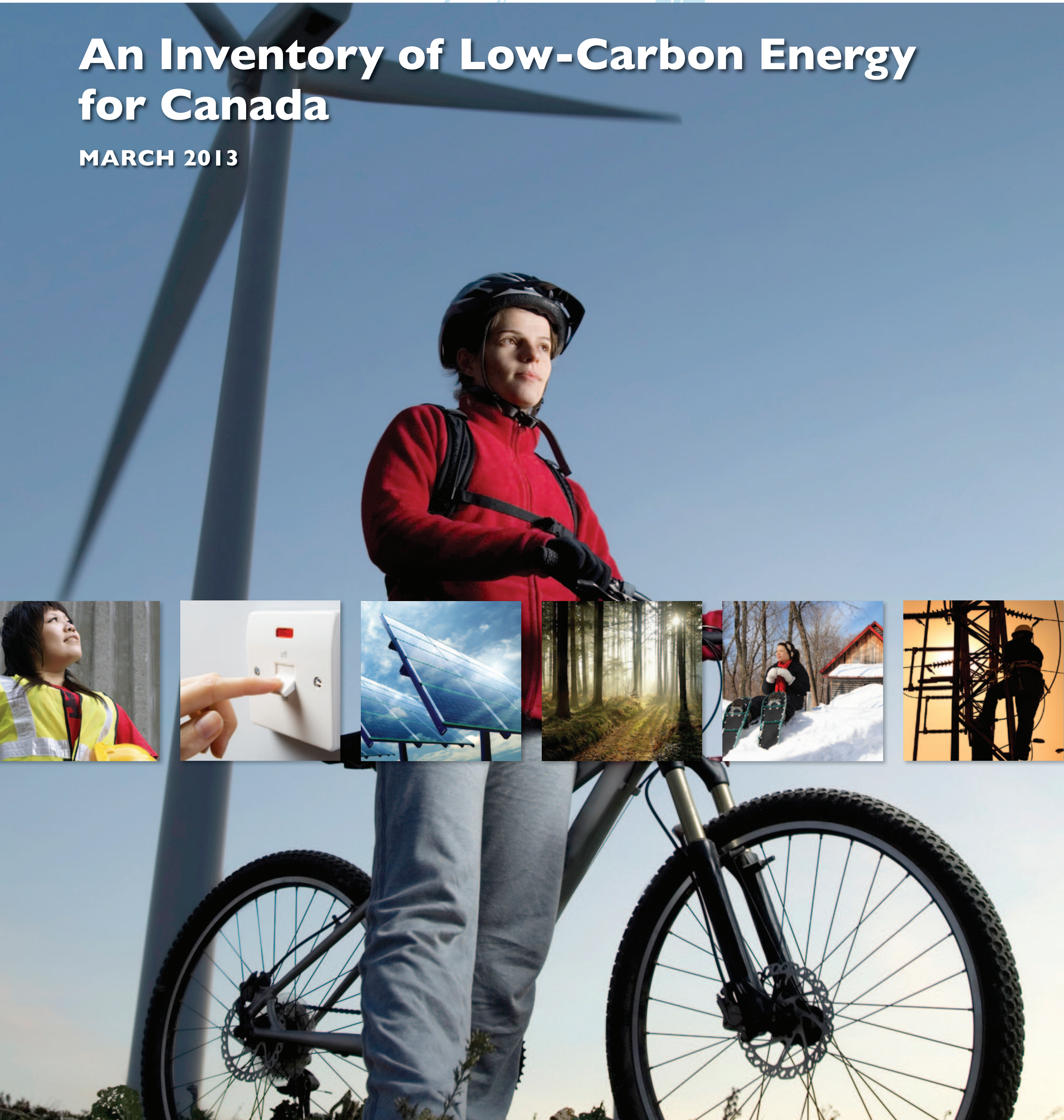
The Trottier Energy Futures Project

An Inventory of Low-Carbon Energy for Canada

MARCH 2013



An Inventory of Low-Carbon Energy for Canada

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An Inventory of Low-Carbon Energy for Canada

LIST OF ABBREVIATIONS

Capacity factor	The ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time.
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization (or Usage)
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CPV	Concentrated Photovoltaic
EJ	Exajoule
FIT	Feed-in Tariff
GHG	Greenhouse Gas
GJ	Gigajoule
GW	Gigawatt
GWh	Gigawatt-Hour
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km	Kilometre
kW	Kilowatt
kWh	Kilowatt-Hour
Mt	Megatonne
MW	Megawatt
MWh	Megawatt-Hour
Odt	Oven-Dry Tonne
PJ	Petajoule
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
Reserve	The share of a resource that is known to exist and can be extracted with current technology at specified prices.
Resource	The total amount of a resource that is believed to exist, without consideration of whether it could ever be extracted.
SHW	Solar Hot Water
Social Licence to Operate	Ongoing approval within the community or among other stakeholders, or ongoing approval or broad social acceptance, usually applied to resource projects.
TWh	Terawatt-Hour

PREFIXES USED IN METRIC UNITS

Kilo	thousand	10^3
Mega	million	10^6
Giga	billion	10^9
Tera	trillion	10^{12}
Peta	quadrillion	10^{15}
Exa	quintillion	10^{18}





Context

Established in 2009 as a partnership between the David Suzuki Foundation, the Canadian Academy of Engineering, and the Trottier Family Foundation, the objective of the Trottier Energy Futures Project (TEFP) is to chart a course for an 80 per cent reduction in Canada's energy-related GHG emissions by 2050, using 1990 levels of 500 megatonnes (Mt) as a baseline. To inform and support this objective, the Trottier Project has initiated a comprehensive research and modeling effort.

The TEFP is producing a series of background papers to shed light on the current state of knowledge on low-carbon energy futures. This paper offers an overview of the non-fossil sources of energy that could realistically be available to the country by mid-century, given current knowledge of technologies and costs.

The other reports in the TEFP background paper series include:

- *Low-Carbon Energy Futures: A Review of National Scenarios*, released in January, 2013
- *Canadian Greenhouse Gas Emissions – Current Patterns and Historical Trends,* forthcoming
- *Toward a Low-carbon Future for Canada: Defining the Challenges,* forthcoming.

Against the scope and complexity of the energy system shown in Figure ES1 (overleaf), this paper focuses on the left side of the diagram, Energy Production. It presents an overview of potential sources of low-carbon energy, and reviews the feasibility of existing harvesting technologies.

This paper will help to inform the final TEFP report, which will present scenarios of how Canada could remain prosperous while making the transition to a sustainable, low-carbon energy future through increased efficiency, greater reliance on renewable and low-carbon fuels and electricity, and changes in the way we use energy.

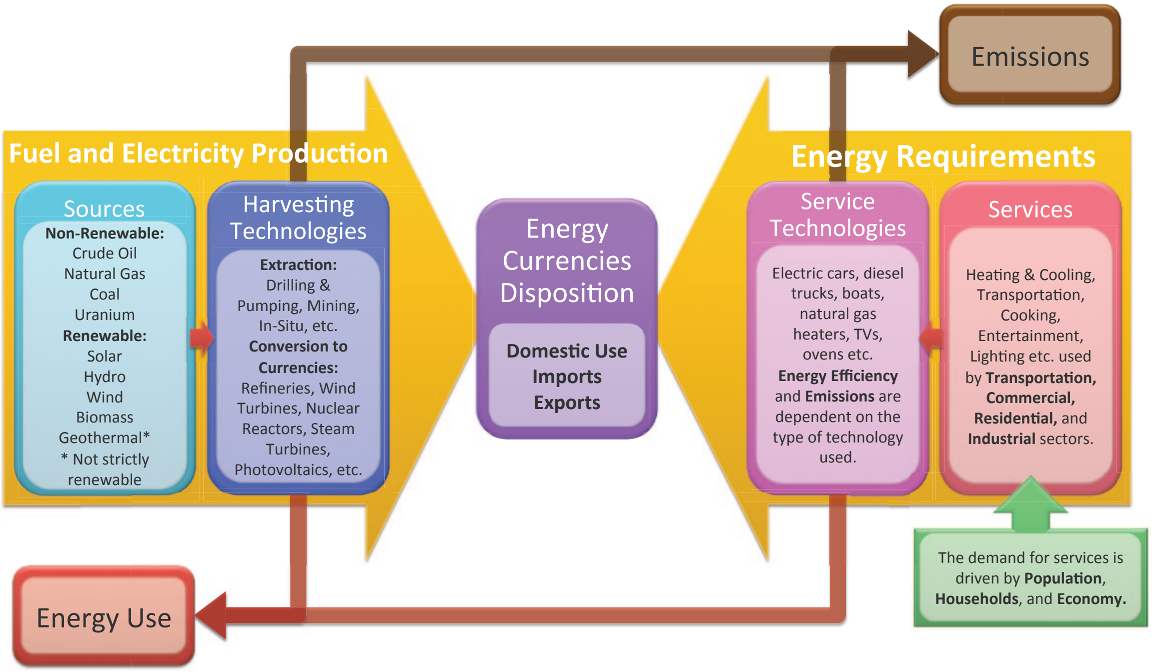


Figure ES1 Canada's Energy System, Institute for Sustainable Energy, Environment and Economy, University of Calgary, 2012, inspired by Sanborn Scott's five-link architecture of an energy system, some labels revised to match Trottier Project analytic framework





Executive Summary

The purpose of this paper is to:

- Summarize the best available research on the quantities of sustainable, low-carbon energy that could plausibly be available to Canada by 2050
- Review the technology and cost constraints that may arise with the deployment of low-carbon energy sources
- Identify the broader system challenges that will have to be addressed for the successful acceleration of Canada's non-fossil resources.

To achieve these objectives, we surveyed the literature on a wide spectrum of low-carbon energy supply technologies, with a focus on four questions:

1. What quantities of fuel or electricity could be available in Canada from each of the major low-carbon sources by 2050, based on today's technology and supply assessments?
2. What are the principal technology options for harvesting the resource?
3. What are the technical limitations on the ability to harvest or deploy the resource?
4. What information is available about the estimated costs of deploying the various technologies?

Summary of Findings

The review concentrates primarily on options that are technologically viable now or very likely to be in the near future to avoid over-reliance on research, development, and demonstration timelines that could shift in the future. The scope of this paper excludes energy efficiency and changes in the demand for energy services, both of which will be central components of a low-carbon energy future but are addressed elsewhere in the Trottier Energy Futures Project research and analysis program.

Figure ES2 shows Canada's domestic consumption of primary energy from 1926 to 2009. It provides context for Table ES3, which summarizes key findings for each of the major low-carbon energy sources we reviewed.

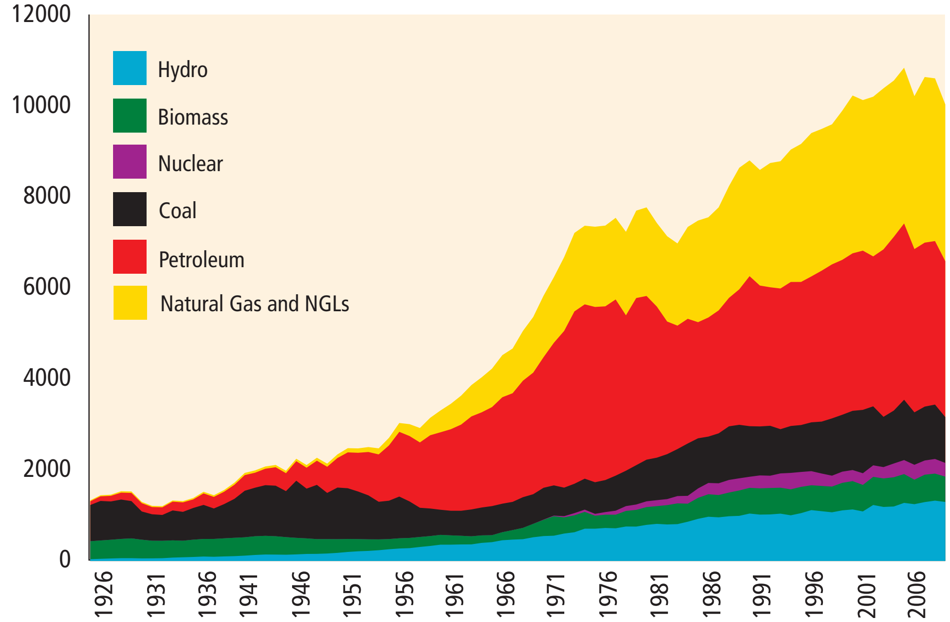


Figure ES2. Domestic Consumption of Primary Energy, 1926-2009
(Data compiled by Trottier staff from Statistics Canada and Steward (1978))

Table ES3 Summary of Key Findings

Solar PV	The potential for solar energy production in Canada is immense. With Canada's large land area and average insolation of 130 watts per square metre in the more southern latitudes, the deployment of photovoltaic systems in the coming years will not be restricted by available energy. Our analysis also indicates that technological development and cost per kWh will be secondary constraints. The more likely limiting factors include grid integration capability and the amount of unobstructed space (rooftops, land, or south-facing facades) that can be dedicated to solar production. Solar PV must also share the total limit on non-dispatchable power with wind. Given these considerations, we estimate the upper limit on plausible annual supply of photovoltaic electricity in Canada by 2050 at 150 TWh (540 PJ). Actual deployment will likely be much lower.
Passive Solar and Solar Thermal	Passive solar and solar thermal are technologies that straddle the boundary between supply and demand. Passive solar is a demand–side reduction technique that will be an essential piece of a longer-term transition to net-zero energy buildings. Passive solar has the potential to supply 20 to 40 per cent of business-as-usual heating demand, and solar thermal could contribute 40 to 80 per cent of energy needs in specific, targeted applications.
Wind Energy	Wind energy's quantitative contribution to meeting Canada's energy needs in 2050 will not be constrained by the size of the resource, but by system integration considerations related to variability, energy storage capabilities, location, and the transmission capacity of the current electrical grid. Given these considerations, we estimate the upper limit on plausible, annual supply of wind electricity in Canada in 2050 at 150 TWh (540 PJ), a fraction of the theoretical potential, with actual deployment probably less than half of this total.

Table ES3 Summary of Key Findings (continued)

Large Hydro	Hydropower currently accounts for more than half of Canada's electricity production, the vast majority supplied by large-scale hydro. Large-scale hydro has an installed capacity of 73,000 MW with an addition 17,000 MW in development, and supplies about 375 TWh (1,350 PJ) per year of electricity in Canada. The untapped potential for future development is approximately 160,000 MW, representing theoretical generation potential of more than 700 TWh (2,520 PJ) per year. Public opinion and environmental regulation may limit future expansion, since large-scale hydro projects have significant impacts on local environments and communities. Even so, 50 to 100 TWh (180 to 360 PJ) of additional annual electricity production from hydropower is plausible by 2050.
Small and Low-Head Hydro	The role of small and low-head hydro is increasing in Canada. Natural Resources Canada estimates the potential at 14,270 MW and 20,000 MW, respectively, but much of this development is currently constrained by economics and geographic location. Like large-scale hydro plants, future small hydro developments may be limited by public opposition. While they do not use large reservoirs, they cause other environmental impacts, primarily in the form of land disruption, road access requirements, forest cuts for power lines, and facility construction.
Nuclear	The potential for nuclear power to contribute to Canada's low-carbon energy supply is not constrained by any practical limitations on the country's uranium reserves or technological expertise. The primary constraints come down to social acceptance and system costs. Nuclear generation often draws strong opposition, and it is expensive, with costs currently trending up. There are currently 18 reactors in Canada with total installed capacity of 13.4 GW generating about 90 TWh (324 PJ) per year. Replacing or refurbishing this capacity by 2050, plus doubling it with 15 new 1000-MW plants, would bring nuclear output to 200 TWh (720 PJ).
Biomass	Biomass currently supplies five to six per cent of Canada's domestic primary energy, mostly as wood used in the pulp and paper industry. It is also moving into the wider economy as a feedstock for electricity generation and transportation fuels. Preliminary analysis by the TEFP points toward some scenarios in which biomass use for energy could increase three- to six-fold by 2050. We have calculated total potential output of 7,600 PJ of primary energy from biomass feedstocks, but the data support a range from 3,000 to 12,000 PJ, depending on assumptions about everything from silviculture practices to the impact of insects and forest fires on wood supplies. It is important to understand the sustainable supply of biomass that can be grown and allocated for energy applications by 2050 in the context of numerous competing uses for the biomass.
Geothermal	Canada does not have an extensive history of exploiting geothermal energy for power production. Current applications are primarily limited to harnessing low-grade resources through heat pumps.
Wave	The theoretical quantity of wave energy along Canada's coasts is immense, but various practical obstacles limit the actual, usable power from waves to a small fraction of the potential. Key factors include harsh maritime conditions, conversion losses, environmental and social factors, and significant seasonal variations. The National Round Table on the Environment and the Economy estimated the realizable potential for wave power at 10,100 to 16,100 MW, which at 25 per cent capacity factor equates to 22 to 35 TWh (79 to 102 PJ).
Tidal	The theoretical potential of the tidal energy resource in Canada is very large, with the best sites for tapping tidal currents located in coastal lagoons, estuaries, and narrow passages between islands. Most of the potential sites are located in areas affected by sea ice, and most of the largest sites are far from Canada's electrical power grid, or from the main centres of demand for electricity. The Canadian Hydraulic Centre estimated total mean potential power of 42.2 GW, but only about 15 per cent of this is considered extractable; 6,300 MW at a 25 per cent capacity factor would yield 14.5 TWh (52 PJ) per year.

Conclusions

Canada has vast renewable energy resources in the form of hydropower, solar, wind energy, and biomass, as well as geothermal, wave, and tidal resources that are many times larger than current or projected levels of total fuel and electricity consumption. The country also has uranium resources that are very large relative to domestic requirements. So Canada's prospects for a transition to a "post-petroleum" energy future are not limited by a physical shortage of renewable and carbon-free energy sources.

However, these estimates of potential availability are not in themselves sufficient to determine that a technology can or should be widely adopted. A variety of factors, some of which fall outside the scope of this report, will continue to shape and reshape any assessment of Canada's practically attainable, low-carbon energy potential, including:

- Improved mapping, measurement, and remote sensing techniques
- Fluctuations in the relative cost of different fuels and electricity
- Changing demand patterns in both domestic and international markets
- Opportunities to integrate two or more low-carbon energy sources in a single system through smart grids, combined heat and power (CHP) systems, or vehicle-to-grid interfaces
- A variety of factors outside the energy system that can weigh for or against different fuel and electricity options in different contexts
- Business, financing, and logistical innovations necessary for the deployment of new and emerging technologies.

In addition to the individual resource assessments, two broad conclusions emerged from the review, the first related to the provision of electricity from renewable and low-carbon sources, the second to fuels derived from biomass feedstocks:

First, Canada has an abundance of ***low-carbon options for producing electricity***. The challenge will be to integrate the various supply sources through a new grid that is more complex, using information technologies to balance:

- Dispatchable and non-dispatchable generation
- Conventional renewable and non-renewable generation
- Energy storage
- Inter-grid transfers
- Responsive demand
- A transmission and distribution infrastructure that supports a high degree of connectivity and multi-directional flows of energy and information.

A successful transition to a low-carbon energy system will depend on significant capital investments in storage, transmission infrastructure, and the backup capacity required to ensure a continuous, reliable electricity supply. It follows that the cost of any particular supply option is not the only factor that determines the relative value of that resource in the overall system. The assurance of an uninterrupted, reliable supply of electricity, and the cost of that reliable electricity, will depend on the cost of the whole system, and the role of each individual generation option can only be determined in that systems context.

Second, ***expanded biofuel*** use in transport is a common theme in most low-carbon scenarios, and in all the ultra-low carbon scenarios reviewed by the Trottier Project.[1] However, the sustainable supply of primary biomass feedstock may be the limiting factor in the growth of biomass-based liquid and gaseous fuels. The total photosynthetic primary productivity of Canadian forest and agricultural lands is large enough, and could be boosted further with new agricultural and silvicultural techniques and technologies, but energy is not the only demand on that biomass, or on the ecosystems in which it grows. The imperative to manage these ecosystems sustainably will limit the amount of primary biomass that can be used for energy.

This inventory of low-carbon energy resources is one of the first steps in mapping a set of comprehensive, integrated scenarios for a sustainable, low-carbon energy system. Ultimately, the prospects for a transition to a low-carbon future depend not so much on the availability of the necessary physical resources, or on the cost and performance of any particular technology, as on the ***integrative strategies*** that combine the individual elements in systems that can deliver affordable, reliable, sustainable energy services. This system view is a central focus for the Trottier Energy Futures Project's ongoing scenario development and modeling.






Contexte

Fondé en 2009 dans le cadre d'un partenariat regroupant la Fondation David Suzuki, l'Académie canadienne du génie et la Fondation familiale Trottier, le Projet Trottier pour l'avenir énergétique (PTAE) a pour but de tracer la voie en vue d'une réduction de 80 pour cent des émissions de gaz à effet de serre (GES) reliées au secteur énergétique d'ici 2050 par rapport aux niveaux de 1990, année référence où les émissions se sont élevées à 500 mégatonnes (Mt). Le projet Trottier a entamé un grand effort de recherche et de modélisation afin de documenter et d'atteindre cet objectif.

Le PTAE produit une série de documents d'information pour faire la lumière sur l'état actuel des connaissances sur les possibilités d'un avenir énergétique à faible intensité de carbone. Le présent document offre un aperçu des sources d'énergie non fossiles auxquelles les Canadiens pourraient vraisemblablement avoir accès au milieu du siècle, compte tenu des connaissances actuelles des coûts et des technologies connexes.

La série de documents d'information publiés par la PTAE comprend les titres suivants (en anglais seulement pour l'instant) :

- *Low-Carbon Energy Futures: A Review of National Scenarios* (Avenirs énergétiques à faible intensité de carbone : Examen de scénarios nationaux), publié en janvier 2013.
- *Canadian Greenhouse Gas Emissions – Current Patterns and Historical Trends (*Émissions canadiennes de gaz à effet de serre – Situation actuelle et tendances historiques*), à venir.*
- *Toward a Low-carbon Future for Canada: Defining the Challenges* (Vers un avenir à faible intensité de carbone au Canada : Cerner les défis), à venir.

En ce qui concerne la portée et la complexité de la filière énergétique illustrée à la figure SE1, le présent document se concentre sur le côté gauche du diagramme, soit la production d'énergie. Il présente une vue d'ensemble des sources potentielles d'énergie à faible teneur en carbone et examine la faisabilité des technologies de captage d'énergie actuelles.

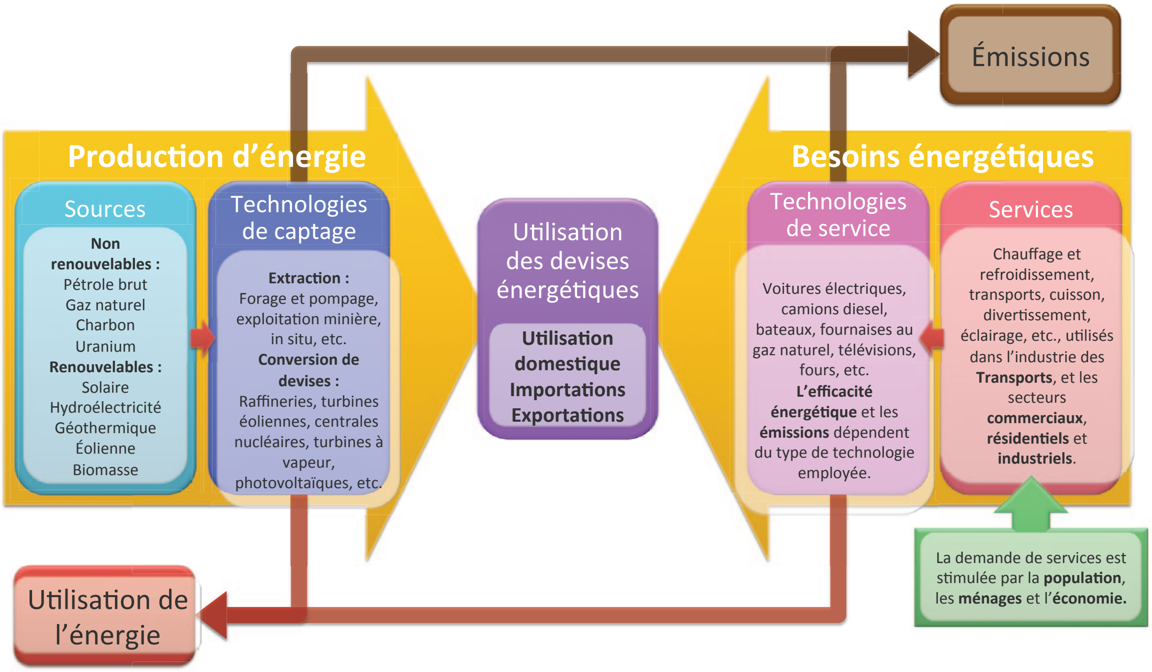


Figure SE1. La filière énergétique du Canada, Institute for Sustainable Energy, Environment and Economy, Université de Calgary 2012. Inspiré de l'architecture d'un système énergétique à cinq liens de Sanborn Scott. Certaines formulations ont été revues afin de correspondre au document d'analyse du Projet Trottier.

Le présent document éclairera le rapport final de la PTAE, qui présentera des scénarios sur la façon d'assurer la prospérité du Canada pendant sa transition vers un avenir énergétique à faible intensité de carbone grâce à une efficacité accrue, à une plus grande dépendance envers l'électricité et les combustibles renouvelables et à faible émission de carbone, et à des changements dans la façon dont nous utilisons l'énergie.

Sommaire exécutif

Le présent document vise les objectifs suivants :

- Résumer les meilleures recherches sur la quantité d'énergie durable et à faible intensité de carbone qui pourrait, en toute plausibilité, être disponible au Canada d'ici 2050;
- Examiner la technologie et les contraintes financières qui pourraient accompagner le déploiement de sources d'énergie à faible intensité de carbone;
- Cerner les grands défis systémiques à relever afin d'accélérer la production des ressources non fossiles du Canada.

Pour atteindre ces objectifs, nous avons passé en revue la littérature portant sur un vaste éventail de technologies d'approvisionnement énergétique à faible intensité de carbone, en cherchant à répondre à quatre questions :

1. Quelle quantité de combustible ou d'électricité chacune des grandes sources à faible teneur en carbone pourrait-elle générer au Canada d'ici 2050, selon les évaluations actuelles de la technologie et des modes d'approvisionnement?
2. Quelles sont les principales options technologiques aux fins du captage de la ressource?
3. Quelles sont les limites techniques restreignant la capacité de capter ou déployer la ressource?
4. Quelle est l'information disponible quant aux coûts estimés du déploiement des diverses technologies?

Résumé des constatations

L'étude se concentre essentiellement sur les solutions qui sont technologiquement viables à l'heure actuelle, ou qui le deviendront très probablement dans un avenir rapproché, afin d'éviter de dépendre excessivement du rythme de progression de la recherche, du développement et de la démonstration, lequel pourrait rapidement changer dans l'avenir. Cet article ne traite pas de l'efficacité énergétique et des variations de la demande de services énergétiques, qui seront tous deux des éléments centraux d'un avenir à faible intensité de carbone; ces sujets sont d'ailleurs traités dans un autre volet du programme de recherche et d'analyse du Projet Trottier pour l'avenir énergétique.

La figure SE2 démontre la consommation domestique d'énergie primaire au Canada de 1926 à 2009. Elle nous permet de mettre en contexte le tableau SE3 qui résume les principales constatations associées à chacune des sources d'énergie à faible teneur en carbone que nous avons étudiées.

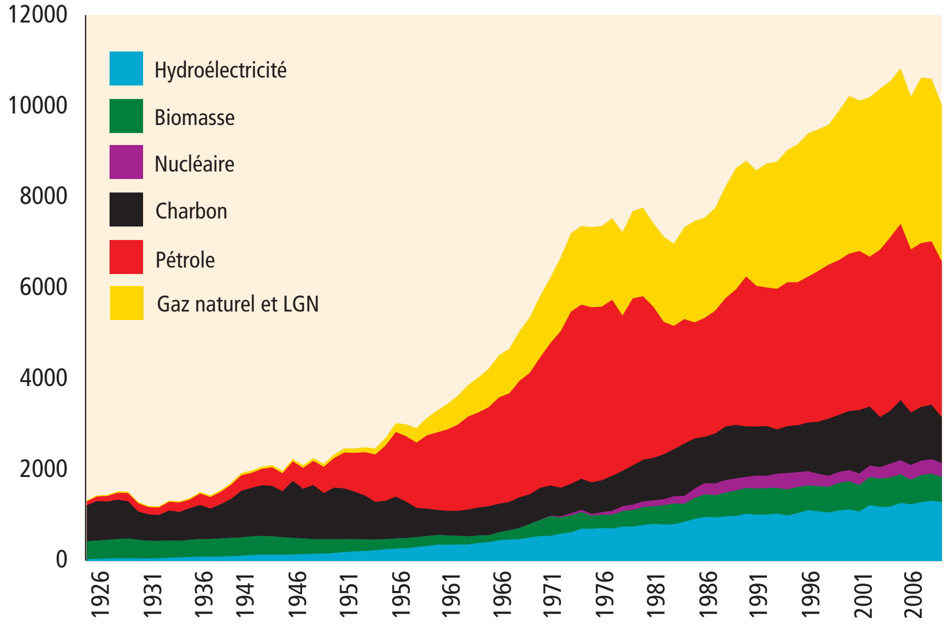


Figure SE2 : Consommation domestique d'énergie primaire de 1926 à 2009
(Données compilées par l'équipe du Projet Trottier à partir d'information de Statistiques Canada et Steward (1978))

Tableau SE3 Résumé des principales constatations

Énergie solaire photovoltaïque	Le Canada possède un immense potentiel de production d'énergie solaire. Compte tenu de son vaste territoire et de l'insolation moyenne de 130 watts par mètre carré dans les latitudes les plus au sud, il est assuré que le déploiement de systèmes photovoltaïques ne sera pas limité par l'énergie disponible au cours des prochaines années, bien au contraire. Notre analyse indique également que le développement technologique et le coût par kWh ne seront que des contraintes secondaires. Au nombre des facteurs limitatifs les plus probables, mentionnons la capacité d'intégration du réseau et la quantité d'espace libre (toits, terrains ou façades orientées vers le sud) pouvant servir à la production d'énergie solaire. L'énergie solaire photovoltaïque doit également partager avec l'énergie éolienne la limite totale d'énergie ne pouvant être acheminée. Compte tenu de ces considérations, nous estimons à 150 TWh (540 PJ) la limite supérieure de l'approvisionnement énergétique annuel plausible de l'électricité photovoltaïque au Canada en 2050. Le déploiement réel sera probablement beaucoup plus faible.
Énergie solaire passive et énergie solaire thermique	L'énergie solaire passive et l'énergie solaire thermique sont des technologies qui chevauchent la frontière entre l'offre et la demande. L'énergie solaire passive est une technique de réduction de la demande qui sera appelée à jouer un rôle essentiel dans la transition à plus long terme vers des bâtiments à consommation énergétique nette zéro. L'énergie solaire passive a le potentiel de réduire la demande courante de chauffage de 20 à 40 pour cent, alors que l'énergie solaire thermique pourrait combler de 40 à 80 pour cent des besoins énergétiques associés à certaines applications précises et bien ciblées.
Énergie éolienne	La contribution quantitative de l'énergie éolienne à la satisfaction des besoins énergétiques du Canada en 2050 ne sera pas limitée par la disponibilité de la ressource, mais bien par des considérations relatives à l'intégration des systèmes : la variabilité, les capacités de stockage d'énergie, l'emplacement et la capacité de transmission du réseau électrique. Compte tenu de ces considérations, nous estimons que la limite supérieure plausible de l'offre annuelle d'électricité éolienne au Canada s'élèvera à 150 TWh (540 PJ) en 2050; notons qu'il ne s'agit que d'une fraction de son potentiel théorique – le déploiement réel représentera probablement moins de la moitié de ce total.
Grandes centrales hydroélectriques	L'hydroélectricité représente actuellement plus de la moitié de la production d'électricité du Canada, dont la grande majorité provient des grandes centrales hydroélectriques. Ces dernières possèdent une puissance installée de 73 000 MW, à laquelle s'ajoutent 17 000 MW en développement, et produisent environ 375 TWh (1,350 PJ) d'électricité par an au Canada. Le potentiel inexploité pouvant éventuellement être mis en valeur est d'environ 160 000 MW, ce qui représente un potentiel de production théorique de plus de 700 TWh (2520 PJ) par année. L'opinion publique et la réglementation environnementale peuvent limiter la multiplication de ce type de centrale, car les grands projets hydroélectriques produisent des effets considérables sur l'environnement local et les communautés des environs. En dépit de ce qui précède, il est plausible qu'une quantité supplémentaire de 50 à 100 TWh (180 à 360 PJ) d'électricité d'origine hydraulique soit produite tous les ans d'ici 2050.
Centrales hydroélectriques petites ou de basse chute	Les petites centrales hydroélectriques ou de basse chute jouent un rôle de plus en plus important au Canada. Ressources naturelles Canada estime leur potentiel à 14 270 MW à 20 000 MW respectivement, mais l'économie et la géographie limitent une grande partie de cette mise en valeur à l'heure actuelle. Comme dans le cas des grandes centrales hydroélectriques, il se peut que l'opposition du public limite la possibilité de lancer de petits projets de mise en valeur de l'hydroélectricité. Bien que ces derniers n'utilisent pas de grands réservoirs, ils provoquent d'autres effets sur l'environnement, notamment la perturbation des terres, les aménagements nécessaires à l'accès routier, les coupes forestières servant au passage des lignes électriques, ainsi que la construction des installations.

Tableau SE3 Résumé des principales constatations (continué)

Énergie nucléaire	Les réserves d'uranium et l'expertise technologique du pays n'imposent aucune limite pratique au potentiel de l'énergie nucléaire dans l'approvisionnement d'énergie à faible intensité de carbone. Les principales limites de ce type d'énergie sont son acceptation sociale et le coût des systèmes nécessaires à sa production. La production nucléaire suscite généralement forte opposition; de plus, son coût, déjà élevé, continue de croître. Le Canada compte actuellement 18 réacteurs ayant une puissance installée totale de 13,4 GW et générant environ 90 TWh (324 PJ) par an. Le remplacement ou la remise à neuf de cette capacité d'ici 2050, en plus de la construction de 15 nouvelles usines d'une capacité de 1 000 MW chacune, porterait la production nucléaire à 200 TWh (720 PJ), soit le double de la production actuelle.
Biomasse	La biomasse fournit actuellement de cinq à six pour cent de l'énergie primaire domestique du Canada, essentiellement sous forme de bois utilisé dans l'industrie des pâtes et papiers. Elle intègre également dans l'économie tout entière en tant que matière première aux fins de la production d'électricité et de carburants de transport. Le PTAE a effectué une analyse préliminaire ayant relevé certains scénarios dans le cadre desquels l'utilisation énergétique de la biomasse pourrait être de trois à six fois supérieure d'ici 2050. Nous avons calculé une production totale potentielle de 7 600 PJ d'énergie primaire à partir de matières premières tirées de la biomasse, mais les données situent la production entre 3 000 à 12 000 PJ selon les hypothèses relatives sur tous les sujets, des pratiques sylvicoles à l'incidence des insectes et des feux de forêt, en passant par les réserves de bois. Il est important de connaître les réserves durables de biomasse qu'on peut cultiver et allouer à des applications énergétiques d'ici 2050 dans le contexte des nombreuses utilisations concurrentes de ce type d'énergie.
Énergie géothermique	Le Canada n'a pas une très longue feuille de route en ce qui concerne l'exploitation de l'énergie géothermique aux fins de la production d'électricité. Les applications actuelles se limitent essentiellement à l'exploitation de ressources de faible qualité au moyen de pompes à chaleur.
Énergie houlomotrice (vagues)	La quantité théorique de l'énergie houlomotrice le long des côtes du Canada est immense, mais divers obstacles pratiques limitent la puissance réellement utilisable des vagues à une petite fraction de son potentiel. Au nombre des facteurs clés figurent les conditions maritimes difficiles, les pertes en cours de conversion, les facteurs sociaux et environnementaux et les variations saisonnières considérables. La Table ronde nationale sur l'environnement et l'économie a estimé que le potentiel de réalisation de l'énergie houlomotrice est de 10 100 à 16 100 MW, ce qui, à un facteur de charge de 25 pour cent, équivaut à un total de 22 à 35 TWh (79 à 102 PJ).
Énergie marémotrice	Le potentiel théorique de la source d'énergie marémotrice au Canada est très important; les meilleurs sites pour exploiter les courants de marée sont les lagunes côtières, les estuaires et les passages étroits entre les îles. La plupart des sites potentiels sont situés dans des zones où se forme de la glace de mer, et la plupart des grands sites sont éloignés du réseau électrique canadien, ou des centres d'où provient la majeure partie de la demande d'électricité. Le Centre d'hydraulique canadien estime que la puissance moyenne potentielle totalise 42,2 GW, mais à peine 15 pour cent de cette puissance est considérée comme récupérable; une puissance de 6 300 MW à 25 pour cent de facteur de charge donnerait un total annuel de 14,5 TWh (52 PJ).

CONCLUSIONS

Le Canada possède de vastes ressources énergétiques renouvelables sous la forme d'hydroélectricité, d'énergie solaire, d'énergie éolienne et de biomasse, ainsi que des ressources géothermiques, houlomotrices et marémotrices plusieurs fois supérieures aux niveaux actuels ou projetés de la consommation totale de carburant ou d'électricité. Le pays dispose également de ressources d'uranium qui sont très importantes par rapport aux besoins intérieurs. Ainsi, les perspectives du Canada en vue d'une transition vers un avenir énergétique « postpétrole » ne sont nullement limitées par la quantité physique de sources d'énergie renouvelables qui n'émettent pas de gaz carbonique.

Toutefois, ces estimations de la disponibilité potentielle de diverses sources d'énergie ne suffisent pas à elles seules à déterminer la possibilité ou la pertinence d'adopter à large échelle une technologie donnée. Un éventail de facteurs, dont certains s'inscrivent hors du cadre du présent rapport, continueront de façonner et remodeler toute évaluation du potentiel énergétique à faible intensité de carbone qui est réalisable au Canada dans la pratique :

- De meilleures techniques de cartographie, de mesure et de télédétection;
- La fluctuation du coût relatif de l'électricité et de différents carburants;
- Les tendances changeantes de la demande au sein des marchés intérieur et international;
- La possibilité d'intégrer plusieurs sources d'énergie à faible intensité de carbone en une filière unique au moyen de réseaux intelligents, de la production combinée électricité-chaleur ou d'interfaces véhicules-réseau;
- Un éventail de facteurs extérieurs à la filière énergétique peuvent influer négativement ou positivement sur l'emploi de l'électricité ou de divers carburants, selon le contexte;
- Le monde des affaires, le financement et les innovations logistiques sont nécessaires au déploiement de technologies nouvelles ou émergentes.

Outre l'évaluation de chaque ressource, deux grandes conclusions ressortent de l'examen : la première concerne l'approvisionnement en électricité à partir de sources renouvelables et à faible intensité de carbone, alors que la seconde découle des carburants issus de matières premières biologiques :

Premièrement, le Canada possède une abondance de ***solutions à faible intensité de carbone aux fins de la production d'électricité***. La difficulté sera d'intégrer les diverses sources d'approvisionnement dans un nouveau réseau plus complexe en équilibrant les éléments suivants au moyen des technologies de l'information :

- La production pouvant être acheminée et celle qui ne le peut pas;
- La production conventionnelle renouvelable ou non renouvelable;
- Le stockage de l'électricité;
- Les transferts d'un réseau à un autre;
- La demande sensible aux prix;
- Une infrastructure de transmission et de distribution qui peut prendre en charge un degré de connectivité élevé et des flux d'énergie et d'information multidirectionnels.

Une transition réussie vers une filière énergétique à faible émission de carbone nécessite l'investissement de sommes considérables dans le stockage, l'infrastructure de transmission et la capacité de sauvegarde nécessaires pour assurer un approvisionnement sûr et continu en électricité. De ce fait, le coût de toute option d'approvisionnement donnée n'est pas le seul facteur qui détermine la valeur relative de cette ressource dans l'ensemble de la filière. L'assurance d'un approvisionnement sûr et ininterrompu en électricité, ainsi que le coût de l'électricité ainsi fournie, dépendra du coût de toute la filière; le rôle de chaque option de production ne peut être déterminé qu'en tenant compte du contexte de la filière.

Deuxièmement, ***l'utilisation accrue des biocarburants*** dans le secteur des transports est un thème commun dans la plupart des scénarios à faible intensité de carbone, ainsi que dans tous les scénarios à très faible intensité de carbone, étudiés par le Projet Trottier.[2] Cependant, l'approvisionnement durable en matières premières biologiques peut constituer le facteur limitant l'essor des combustibles gazeux et liquide issus de la biomasse. La productivité primaire totale photosynthétique des forêts et terres agricoles canadiennes est assez grande, mais on pourrait l'accroître encore davantage par de nouvelles techniques et technologies agricoles et sylvicoles. Toutefois, cette biomasse, de même que les écosystèmes qui la produisent, n'est pas sollicitée uniquement aux fins de la production d'énergie. Soulignons que la nécessité de gérer ces écosystèmes dans une optique de durabilité limitera la quantité de biomasse primaire pouvant servir à la production d'énergie.

Cet inventaire des ressources énergétiques à faible émission de carbone est l'une des premières étapes de la création d'un ensemble complet de scénarios intégrés en vue d'une filière énergétique durable à faible intensité carbonique. En fin de compte, la perspective d'une transition vers un avenir sobre en carbone ne dépend pas tant de la disponibilité des ressources physiques nécessaires, ou du coût et du rendement d'une technologie donnée, que des stratégies d'intégration qui regroupent divers éléments individuels en filières pouvant fournir des services énergétiques abordables, sûrs et durables. Cette perspective systémique est un aspect central de l'élaboration et la modélisation continues de scénarios dans le cadre du Projet Trottier pour l'avenir énergétique.






Introduction and Scope of this Paper

The Trottier Energy Futures Project seeks to identify energy futures in which Canada reduces its greenhouse gas emissions by 80 per cent compared to 1990 levels. Fundamentally, there are only three types of pathways to this result:

- Switch energy use to ***lower-carbon and carbon-free sources*** of fuel and electricity
- ***Produce and use energy more efficiently*** through improved technologies and systems
- Deliver the amenities we want and need (eg. comfort, access) using ***technologies and techniques that require less energy service*** (eg. heat, mobility).

This paper is called an "inventory" of low-carbon energy because it itemizes the quantities of the different non-fossil energy resources that might reasonably be deployed in Canada by 2050 as part of a broader transition to a low-carbon energy system. This transition would require more than an accelerated deployment of low-carbon energy resources. An 80 per cent reduction in greenhouse gas emissions would also depend on improvements in the efficiency of energy production and consumption, and on more moderate growth in our demand for energy services. These factors are all being considered in the development of the Trottier Project's low-carbon energy scenarios for Canada, but this paper focuses on just one aspect of the wider challenge: The potential supply of fuel and electricity with low or no greenhouse gas emissions.

The scope of this paper is limited to low-carbon or carbon-free primary energy sources like biomass, hydropower, nuclear, and energy from solar, wind, wave, tidal, and geothermal sources. Another low-carbon option is the application of carbon capture and storage (CCS) to fossil fuel production and consumption. CCS and carbon capture and usage (CCU) can reduce but not eliminate the carbon emissions from fossil fuel production and utilization. It is anticipated that the CCS and CCU technologies will play a role in the Trottier Project's scenarios for a low-carbon future, but they fall outside the scope of this paper.

Energy Services vs. Amenities: Are We Looking for Mobility or Access?

The distinction between fuel and electricity, energy services, and fundamental amenities is an important part of the analytical framework used by the Trottier Energy Futures Project, and is described in more detail in a forthcoming background paper in this series, *Canadian Greenhouse Gas Emissions: Current Patterns and Historical Trends*. Demand for fuel and electricity is derived from the underlying demand for energy services: heat at various temperatures, personal mobility, goods movement, motive power, light, information processing, electrochemistry, and telecommunications. In turn, energy services demand is derived from even more fundamental, underlying demand for basic amenities and services, including:

- Comfortable, healthy living and working environments
- Convenient access to employment, food, education, shopping, recreation, and cultural experiences
- The infrastructure, material goods, and means to maintain a quality of life.

For example, for a single driver commuting 60 kilometres to work, the efficiency of the trip depends on the amount of gasoline required to deliver 60 "person-kilometres" of mobility – the energy service. The driver can boost efficiency by getting a more fuel efficient car, driving a bit more slowly, or by carpooling, taking public transit, even walking or cycling. But the energy service – 60 person-kilometres of mobility – stays the same.

But what if that commuter moved closer to their place of work, or telecommuted? These are measures that actually reduce the energy service required – the person-kilometres of mobility – while delivering the same underlying amenity, access to employment.

This distinction between the demand for amenities (in this case, access) and energy services (mobility) is useful in developing scenarios for low-carbon futures. Innovations that are outside the energy sector itself, for example in urban planning and information technology, can reduce the demand for energy services like mobility, which in turn reduces the demand for fuels and electricity.

Energy efficiency – the second of the three pathways for lower carbon emissions – is also outside the scope of this paper, except where it ties in with the identification of low-carbon energy resources. All the low-carbon scenario analyses we have reviewed[3] identify a dramatic increase in energy efficiency as a prerequisite for a low-carbon future, and the potential is particularly great in Canada, where more than half of the usable energy in fossil fuel production is lost before it reaches its intended end use. However, while energy efficiency improvements will figure prominently in the TEFP low-carbon energy scenarios, this paper focuses strictly on the supply-side potential for low-carbon fuels and electricity.

Nor does this paper address the sustainability criterion. Recent experience with the development of biomass-based ethanol serves as a reminder of the problems caused by focusing exclusively on a single objective at the expense of an integrated approach that considers the environmental, social, and economic dimensions of sustainability. The Trottier Energy Futures Project is interested in energy futures that are both low-carbon and sustainable.

A Sustainable, Low-Carbon Energy Future

Although this report focuses on Canada's low-carbon energy options through 2050, the objective of the Trottier Energy Futures Project is to identify futures that are both low-carbon and sustainable.

With the possible exception of energy efficiency, no low-carbon technology can be considered entirely sustainable after fully accounting for its life cycle impacts. It follows that sustainability is *an emergent property of an energy system*, and can only be understood based on the behaviour of the system as a whole. Natural energy systems point to the following key features that would distinguish a sustainable technological energy system:

- *No waste:* Energy sources are matched in scale and thermodynamic quality to end use demands. Materials are recycled. There are no wasted residuals.
- *Renewable supply sources:* Energy sources are naturally replenished at a constant, foreseeable rate.
- *Environmentally benign:* No toxic substances are generated. Technologies are "safe-fail" and contribute to the health of the ecosystems in which they operate.
- *Diverse and distributed fuel and electricity sources:* Risks and benefits are widely spread, and the system's vulnerability to any single failure is minimized.
- *Resilience:* A distributed energy system can more readily recover from shocks and continue providing energy services in the face of social, economic, and environmental disruptions.
- *Equitable:* System costs and benefits are distributed more equitably across regions, communities, and generations.
- *Embedded social values:* The system favours socially benign technologies and aligns with principles of sustainable development: human welfare, social justice, and self-determination.

Low-Carbon Energy: Technological Feasibility, Cost, and the Social Licence to Operate

The starting point for this paper is a seemingly straightforward question: How much carbon-free[4] energy will be available in Canada in the year 2050?

The physical quantity of available nuclear and renewable energy is many times larger than Canada's current consumption of fuels and electricity. But we also need to know the cost, efficiency, and feasibility of the technologies for making use of that energy before we can assess its ability to displace other, more carbon-intensive sources by 2050.

The Trottier Energy Futures Project is particularly focused on greenhouse gas (GHG) emissions associated with energy production and use. But depending on the end use, Canadians also value many other attributes of different energy forms, including density, storability, portability, versatility, reliability, safety, resilience, dispatchability, convenience, and cleanliness. The value we place on different types of fuel and electricity, and therefore the prices we willingly pay for them, are not determined by the quantity of energy delivered so much as by these other attributes – to the extent that today's energy prices vary by a factor of 50,000. For example, paying $1 for a "AAA" battery translates into a charge of more than $700/kWh for electricity, 7,000 times more than typical retail prices for grid electricity in Canada, and 40,000 times higher than typical retail rates for natural gas.[5]

This reality reframes the question we need to ask about the carbon-free energy available to Canada in the year 2050: ***What is the technological feasibility and cost of converting the available low-carbon energy into valued end use forms or currencies (electricity, heating fuel, transport fuels) and delivering it to end users, when and where they need it?***

This inventory draws heavily on two recent, comprehensive reviews of renewable energy technologies and costs: the IPCC Special Report on Renewable Energy[6] published in 2011, and the Renewable Electricity Futures Study[7] published by the U.S. National Renewable Energy Laboratory (NREL) in 2012. In addition to their own assessments, both studies reviewed hundreds of sources covering current and projected technology performance and costs.

Two important considerations shape any discussion of technology costs:

- The delivered cost of energy using various low- or higher-carbon technologies depends on much more than capital and operating costs. The full calculation depends on interest (discount) rates, technology performance, capacity factors, longevity, and costs associated with delivery infrastructure (eg. the electric grid, road and transit infrastructure).
- Information and control technologies will contribute to much tighter integration among the technologies that work together to meet energy service demands. The traditional lines between supply and demand will become blurred, and a system context will be required to assess the costs and benefits of individual technologies.

In the electricity system, in particular, different supply sources have individual attributes that result in their playing different roles in system operation and delivery of reliable electricity to end users. More broadly, as in a system based on higher-carbon, non-renewable energy sources, the cost of a continuous, reliable supply of electricity depends not only on the unit production costs of the various sources, but on the cost of transmission, distribution, responsive demands, energy storage, inter-grid transfers, wheeling,[8] and on how all of these interacting parts operate together as a system.

Future capital costs are particularly uncertain at a time when the low-carbon energy technologies are at different stages of evolution. Photovoltaic electricity is a prime example of a technology whose costs have fallen so rapidly that projections published only a few years ago are obsolete. While continued capital cost reductions are all but certain, they cannot and will not continue at the recent historical rate, so cost projections should be based on engineering assessments, not extrapolations. By contrast, wave energy technologies are still in the early stages of development, costs are still relatively high, the development path is not yet clear, and even engineering assessments of future capital costs and performance are highly uncertain.

But engineering performance and costs are not the only factors that will determine the role of low-carbon energy options. The technical and economic potential of a particular energy supply technology may well be outweighed if a project reaches the limit of its *social licence to operate.*[9] At one time or another, most of the fuel and electricity options covered by this review have been subject to some degree of public concern or opposition. The strength of that response, and the transparency with which project proponents address it, will sometimes be decisive factors that go beyond engineering and cost assessments.

Historical Energy Use in Canada

How much energy in a PJ?

A petajoule is 1015 joules of energy. A single PJ is equivalent to 278 million kilowatt-hours of electricity, enough to power more than 25,000 households, or 29 million litres of gasoline, enough to keep 10,000 typical Canadian cars on the road for a year.

Like other industrial economies, Canada gets most of its energy from fossil fuels – oil, gas, and coal – and this dependence has been building up for many decades, as shown in Figure 1. Counting only their direct consumption of fuel and electricity, Canadian households and businesses use more than 7,000 PJ of energy each year, but that calculation excludes the energy required to *carry* energy from production site to end users. Add power plant losses and energy consumed by the oil and gas industry itself, and total domestic primary energy consumption is about 10,000 PJ per year, broken down by source in Figure 2.[10]

More than three-quarters of Canada's domestic supply of primary energy comes from fossil fuels. The other 22 per cent comes from "carbon-free" sources,

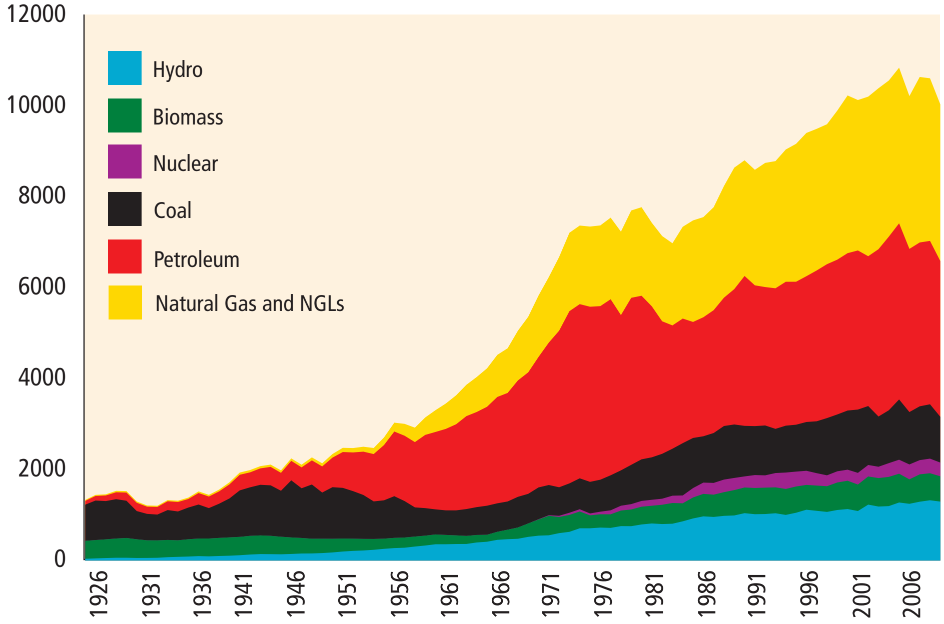


Figure 1. Domestic Consumption of Primary Energy, 1926-2009
(Data compiled by Trottier staff from Statistics Canada and Steward (1978))

including hydroelectricity (13 per cent), biomass (six per cent, most of it biomass used by the pulp and paper industry), and nuclear generation (three per cent)[11]. In low-carbon energy futures – in which energy-related greenhouse gas emissions are reduced by 80 per cent from 1990 levels, to an annual total of about 100 Mt CO_2e – the primary energy supply would have to be dominated by carbon-free sources. The total requirement for carbon-free energy in such futures will depend on population and economic growth rates, changes in consumer preferences and industrial structure, and the extent to which Canadians reduce their demand for fuels and electricity.

Canada currently produces about 2,000 PJ per year of carbon-free energy, out of total domestic primary energy consumption of about 10,000 PJ. Before allowing for future growth in demand – and presuming aggressive electrification, an overall doubling of efficiency, and a switch to natural gas for all residual fossil fuel use – supplies of carbon-free energy would have to increase by at least 1,000 PJ to bring fossil fuel emissions below the 80 per cent GHG reduction target. Factor in growth, and Canada would need even more new carbon-free energy, perhaps up to 3,000 PJ or more, to stay below the 100 Mt CO_2e target. The question of how much carbon-free energy will be required to meet the 80 per cent reduction target is the focus of ongoing analysis and modeling by the Trottier Energy Futures Project.

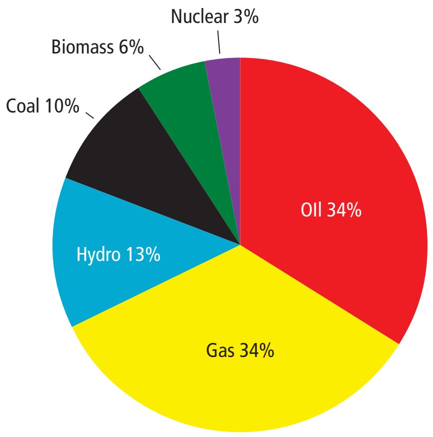


Figure 2. **Primary Energy in Canada, 1926-2009**
(Data based on Statistics Canada, *Report on Energy Supply and Demand*, Catalogue 57-003, 2009.)

Low-Carbon Energy Sources

Solar Photovoltaic

In the southern latitudes of Canada, solar insolation is in the range of 130 watts per square metre, so simple arithmetic tells us the quantity of available solar energy is practically limitless compared to the demand for energy services. Solar production is not restricted by available energy, but by constraints such as the unobstructed space (rooftops, land, or south-facing facades) dedicated to solar production, grid integration capability, industry development, and the rate at which costs can be driven down over the next 20 years.

Photovoltaic cells use semiconductors to convert solar radiation into direct current electricity. In a photovoltaic system, cells are arranged in a solar panel, typically rated up to 200 watts, to produce useable energy at scale. Panels are then arranged in arrays to produce commercial energy or power large buildings. With today's technology, conversion efficiencies in PV cells range from five to 26 per cent.[12] Efficiencies as high as 40 per cent are possible with emerging technologies such as concentrating PV (CPV) systems, which use optics to concentrate incoming solar radiation.[13]

Solar PV arrays can be mounted on rooftops, integrated with buildings, or mounted on the ground as dictated by land use. The electricity they produce can be dispatched to a utility or dedicated for use in local buildings or commercial operations. Total potential generation would be a function of the availability of suitable roof space and the amount and type of land devoted to solar energy production and its proximity to the grid. The Ontario Feed-in Tariff (FIT) program, for example, restricts deployment of ground-mounted solar PVs to Class 3 or higher agricultural land and unused industrial land.

The cost of producing electricity from photovoltaic systems is made up almost entirely of the initial capital cost; operation and maintenance costs are relatively insignificant. There are two components to the initial capital cost: the photovoltaic modules themselves, and the balance-of-system (BOS) costs, including racks, inverters, controls and instrumentation, and labour costs for installation.

The cost of producing photovoltaic electricity is on a steep decline, so that cost benchmarks in projections from only two to three years ago are being achieved decades earlier than predicted.[14] The technology is already cost-competitive in some markets, and under some circumstances.[15] According to the IPCC, module costs dropped from $22/watt (W) in 1980 to less than $1.5/watt by 2010, and total system costs, including BOS and installation, were as low as $2.72/watt by 2009.[16] In a comprehensive review and outlook for photovoltaic costs in 2012, the U.S. National Renewable Energy Laboratory (NREL) reported that module costs had reached $1.25/watt by the end of 2011.[17] Both module and BOS costs vary with system size, with small rooftop systems costing more per watt than utility-scale installations; NREL estimated total system costs from $4-$6/watt in 2010, depending on the size and type of system. The NREL study also included a detailed analysis of the outlook for future PV capital costs, summarized in Table 1.

Table 1. NREL Historical (2010) and Projected PV Capital Costs in 2050[18]

	RANGE OF TOTAL PV SYSTEM COST (2009$/WATT)			
SYSTEM TYPE	2010	2020	2030	2050
Residential Fixed Tilt Rooftop	6.01–6.50	3.15–3.78	2.25–3.33	2.00–2.96
Commercial Scale, Fixed Tilt	4.82–5.15	2.40–3.36	2.00–2.98	1.80–2.64
Utility Scale, Single Axis Tracking	4.02	2.20–2.53	1.90–2.33	1.70–2.04

The NREL projections assume no technological breakthroughs, only incremental, evolutionary progress in achieving specified performance improvements and cost reductions in existing technologies. By mid-2012, current costs were already below the 2010 totals, and the NREL conclusions reflected the widely-held view in the industry that current PV capital costs could be reduced by 50 per cent without technological breakthroughs.[19, 20] How these capital costs translate into costs per kilowatt-hour (kWh) of electricity will depend on the interest rate or discount rate on capital, the amortized lifetime of the system, and the volume of electricity produced, all of which will vary. Table 2 illustrates how the cost per kWh of electricity varies for systems over a range of capital costs, discount rates (3 per cent and 5 per cent), and annual outputs typical for Canadian conditions (1.1 and 1.5 kWh per kW), assuming a 20-year amortization.

The dollars per kilowatt-hour figures in the final column of Table 2 reflect only the cost of producing the electricity, not the additional costs of delivery to final end users. There are no delivery costs if the electricity is used on-site, but integration with transmission and distribution infrastructure will involve additional capital and operating costs.

Table 2. Photovoltaic Electricity Costs for a Range of Capital Costs, Discount Rates and System Outputs

Capital cost in $/watt	Discount rate	Annual kWh per kW capacity	$/kWh
6	5%	1.1	0.44
3	5%	1.1	0.22
3	3%	1.5	0.13
2	5%	1.1	0.15
2	3%	1.5	0.09
1.7	5%	1.1	0.12
1.7	3%	1.5	0.08
1	5%	1.1	0.07
1	3%	1.5	0.04

The value of any kilowatt-hour to electricity system operators also depends on other attributes of the electricity supply and their impact on the cost of maintaining a reliable electricity supply. Photovoltaic electricity is only produced when the sun shines. If it is not needed when it is produced, it can be stored, but this carries additional cost. Moreover, when system demand cannot be met by other dispatchable renewable sources or storage, or moderated by demand response or imports from neighbouring grids, the system operator must turn to expensive, short-term generating capacity, such as a natural gas peaking plant.

So deployment of photovoltaic systems over the next several decades will not likely be constrained by the size of the resource, the technological potential, or even the simple levelized cost per kWh. The pace of deployment will more likely depend on the role that develops for distributed, non-dispatchable generation in an emerging grid, and the trade-off between the value photovoltaic sources will command in the future grid and the value those same solar power systems will have to consumers "behind the meter".

Non-dispatchable, variable sources of electricity such as photovoltaics can present challenges to the management of the supply/demand balance in traditional grids.[21] A combination of increased storage, smart grid applications, and automated control of demand and supply will be needed to accommodate the larger role for variable distributed generation sources envisaged in most low-carbon future scenarios. In this vein, system operators in most provinces are accustomed to managing variability on the demand side, and are learning to manage a varying supply as well.

In the 2007 report of its Energy Pathways Task Force,[22] the Canadian Academy of Engineering concluded that "Canada will not be a leader in the massive technology development efforts that will be needed" to integrate PVs with the centralized power grid. However, there is at least one precedent for a higher degree of integration: Germany produces about 20 TWh per year from 30 GW of building- and ground-mounted solar PV. This is still less than five per cent of annual electricity consumption in Germany, but solar PV is growing faster than any other generation source and often provides 50 per cent of the country's summer peak power,[23] having deployed this potential in 15 years through feed-in tariffs and grid integration policies.[24] The cost of solar PV in Germany has been cut in half over that period.

The land requirements for this scale of solar development are modest. As a rule of thumb, the average non-tracking, flat panel PV system in southern Canada generates about 100 kWh per year for every square metre of collector area. So if Canada were to develop, say, 75 TWh of solar generation potential – a very ambitious scenario – relying entirely on ground-mounted solar systems and solar "farms", the entire undertaking would require about 750 square kilometres of land. This is equivalent to the area occupied by the City of Edmonton, or the total area that has been disturbed to date by surface mining of oil sands in Alberta,[25] and it is much smaller than the 58,000 square kilometres occupied by hydroelectric dam reservoirs across the country.[26] Annual electricity production from hydroelectric dams and associated generating stations averages about 6.2 kWh per square metre of reservoir, about 15 times lower than the output of a typical solar array operating in Canadian conditions. It also seems certain that some of the photovoltaic capacity, perhaps most of it, would be located on existing rooftops; in 2010, NRCan estimated that building-integrated photovoltaics on homes and commercial buildings could generate 72 TWh.[27]

The greenhouse gas emissions incurred in solar cell production depend on the energy system in the jurisdiction where manufacturing takes place. However, even in jurisdictions with GHG-intensive electricity production, emissions from the production of solar PV are significantly lower than for other electricity sources. Overall, the use of solar PV reduces GHG emissions, criteria pollutants, heavy metals, and radiation by 80 to 98 per cent compared to the conventional generation technologies they could replace.[28] As future electricity supplies become more sustainable in any future low-emission scenario, life cycle emissions are further reduced.

The physical size of the solar resource in southern Canada is too large to be meaningful as an estimate of realizable potential. In 2010, a University of Toronto study calculated photovoltaic potential of 152 TWh, including 119 TWh for roof-mounted arrays and 33 TWh for building facades.[29] The NREL analysis of high-penetration renewable electricity futures for the United States illustrated the technical feasibility of non-dispatchable renewable electricity (wind and solar) supplying up to 50 per cent of U.S. electricity needs by 2050. On this basis, and assuming that Canada's electricity consumption in a low-carbon future would be at least 600 TWh per year in 2050, we have estimated the upper limit of potential solar photovoltaic electricity supply at 150 TWh.

Table 3. An Inventory of Low-Carbon Energy for Canada: Photovoltaics in 2050

Potential	150 TWh/540 PJ
Principal Technology Options	Ground-mounted, roof-mounted, and building-integrated photovoltaic systems
Technical Limitations	Potential load balancing challenges for system operators as the output of solar and wind generation increases Seasonal and hourly variations in capacity factors
Cost Factors	Size dependent. IPCC predicts another 50% price drop by 2020,[30,31] with utility scale systems below $2/W, but capacity factors and system integration costs are all-important.
Environmental/ Social Factors	Land use impacts for ground-mounted systems

Passive Solar, Solar Thermal, and Solar Hot Water

The roots of passive solar technologies were traced back millennia in a detailed chronology published in 1980.[32] In its Special Report on Renewable Energy Sources and Climate Change Mitigation,[33] the IPCC explained that in passive solar heating

> …the building itself – particularly its windows – acts as the solar collector, and natural methods are used to distribute and store the heat. The basic elements of passive heating architecture are high-efficiency equatorial-facing windows and large internal thermal mass. The building must also be well insulated and incorporate methods such as shading devices to prevent it from overheating. Another feature of passive solar is 'daylighting', which incorporate special strategies to maximize the use of natural (solar) lighting in the building.

Globally, the IPCC determined that passive solar techniques could reduce heating demand by 40 per cent in new buildings, 20 per cent in retrofits.

Passive solar is a technology that straddles the boundary between supply and demand. In energy supply and demand analyses, it is frequently treated as a demand reduction technique for residential and commercial buildings, part of the wider range of efficiency options that can sharply reduce demand for fuels and electricity in a sector that represents 40 per cent of total energy consumption in industrialized economies.[34] The IPCC[35] highlighted this characteristic with its description of an industry that is equally about concrete, bricks, windows, and human capacity:

> For passive solar heating, part of the industry capacity and supply chain lies in people: namely, the engineers and architects who must systematically collaborate to produce a passively heated building.

> Close collaboration between the two disciplines has often been lacking in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities.

The analytical and modeling convention used by the Trottier Energy Futures Project represents passive solar as a demand-side measure, within the context of a longer-term objective of net-zero energy buildings.[36]

The IPCC[37] also provided a brief review of solar thermal systems using unglazed, glazed, and evacuated tube solar collectors and relying on water tanks for storage. Solar thermal applications include domestic and commercial space and water heating, cooling (using collector heat to drive an absorption refrigeration cycle), industrial process heat, crop drying, and cooking. At efficiencies of 40 to 70 per cent at full sun, solar thermal systems can meet 40 to 80 per cent of the demand for heat energy in these target applications.

Table 4. An Inventory of Low-Carbon Energy for Canada: Passive Solar, Active Solar Thermal, and Solar Hot Water in 2050

Potential	Passive solar as 20-40% of BAU heating demand (retrofit vs. new), solar thermal as 40-80% in specific target applications
Principal Technology Options	Passive solar construction techniques Unglazed, glazed, and evacuated tube solar collector systems
Technical Limitations	
Cost Factors	Largely site- and design-specific
Environmental/ Social Factors	

Wind

Historically, wind energy was developed as a source of mechanical energy for pumping and grinding, but its current and envisaged future role is as a source of electricity. Low-carbon energy scenarios invariably include an expanded role for electricity in meeting end use energy needs, combined with a move to carbon-free sources of electricity generation, including wind. Wind, however, is a variable source of energy, so its potential contribution will be defined by its connection to conventional and emerging technologies for electricity supply, demand, storage, and system integration that will shape the smart, low-carbon grid of the future.

Wind energy is currently the fastest-growing source of global electricity generation, although it is starting from a very small base and still represents a small contribution to the global supply of electricity. The Canadian Academy of Engineering[38] observed that the use of wind farms to supply electricity to power grids "has increased rapidly in recent years to the point that wind power is a growing component of most power systems that have good wind profiles," though technological improvements are required to address grid integration issues and maximize energy storage.

The Canadian Wind Energy Atlas catalogues wind speeds at heights of 30, 50, and 80 metres above ground for all of Canada and adjacent offshore regions, for four seasons, on a grid with cells of about 4.5 x 4.5 kilometres.[39] On average, wind turbines in Canada generate electricity 70 to 80 per cent of the time, and operate with annual capacity factors in the range of 20 to 40 per cent.[40] Electricity can be generated when wind speeds exceed 13 kilometres per hour (km/h), and most large wind turbines shut down for safety reasons when wind speeds exceed 90 km/h.[41] In general, the strongest wind regimes in Canada are far from major population centres, so a central issue in the development of Canada's wind resources is balancing the higher capacity factors and outputs that can be achieved in remote regimes against the investment in transmission capacity needed to deliver the electricity where it is needed.

The strongest wind regimes in Canada, with feasible wind turbine capacity factors above 50 per cent, extend through northern Quebec, Labrador, Newfoundland, Cape Breton, Prince Edward Island, and the offshore region of Atlantic Canada. Wind turbines can also operate with capacity factors of 30 to 50 per cent off the British Columbia coast, through the southern regions of Alberta, Saskatchewan, and Manitoba, onshore and offshore throughout the Great Lakes region (including all of southwestern Ontario), along the Gaspé Peninsula, in most of Nova Scotia and coastal New Brunswick, and in James Bay and its surrounding watersheds in northern Ontario and Quebec.[42]

As with the solar photovoltaic potential, the physical size of the resource – the energy in the wind over all of Canada – is too large to be meaningful as an estimate of realizable potential, and wind's contribution to meeting Canada's energy needs in 2050 is not constrained by the size of the resource. Although some design improvements have made modern wind turbines more easily integrated, the main technical constraints to further wind generation in Canada are the ability to integrate this variable resource into the grid through the use of energy storage, improved forecasting, and smart grid techniques such as demand response.

Based on analysis and operating experience in OECD countries, the IPCC's Special Report on Renewable Energy Sources and Climate Change Mitigation[43] observed that grid integration of wind energy "generally poses no insurmountable technical barriers and is economically manageable" at up to 20 per cent of annual average electrical energy demand. The more recent NREL analysis of high-penetration renewable electricity futures for the United States illustrated the technical feasibility of non-dispatchable renewable electricity (wind and solar) providing up to 50 per cent of U.S. electricity needs by 2050.[44] On this basis, and assuming that Canada's electricity consumption in a low-carbon future would be at least 600 TWh per year in 2050, we have estimated maximum wind generation at 150 TWh.

NREL's 2012 Renewable Electricity Futures Study estimated overnight capital costs[45] for onshore wind energy in 2010 at $1.98/watt (2009 USD).[46] In contrast to the outlook for solar photovoltaic systems, the NREL study concluded that capital costs for onshore wind would remain flat or decline by only 10 per cent through 2035, then stabilize in the range of $1.80-$2.00/watt (2009USD). This is partly due to anticipated cost increases for steel and other wind turbine construction inputs, but also reflects the assumption that industry research and development will focus on capacity factor improvements rather than capital cost reductions. Even with relatively stable capital costs per kilowatt, capacity factor improvements for a particular wind class will translate into reductions in the cost per kilowatt-hour of wind electricity (see Table 5).

Table 5. Illustrative Wind Electricity Costs for a Range of Capital Costs, Discount Rates, and Capacity Factors for Wind[47]

Capital cost in $/watt	Discount rate	Annual kWh per kW capacity	$/kWh
	Onshore Wind		
2.00	5%	30%	7.0
1.80	5%	30%	6.5
2.00	3%	30%	6.1
1.80	3%	30%	5.6
2.00	5%	40%	5.4
1.80	5%	40%	5.0
2.00	3%	40%	4.7
1.80	3%	40%	4.3
2.00	5%	50%	4.4
1.80	5%	50%	4.1
2.00	3%	50%	3.8
1.80	3%	50%	3.5
	Offshore Wind		
3.00	5%	50%	7.4
3.00	3%	50%	6.5
3.00	5%	60%	6.4
3.00	3%	60%	5.6

Offshore wind turbines are more expensive, typically 50 to 100 per cent more per kilowatt than for onshore projects, but the technology is at an earlier stage of development than onshore systems and significant capital cost reductions are still anticipated. The NREL study estimated that current overnight capital costs of $3.64/watt for offshore wind construction will decrease by 18 to 26 per cent, depending on the rate of technological advancement, before stabilizing between 2030 and 2035. Thus, the overnight capital cost of offshore wind projects is expected to be in the range of $2.70-3.00/watt in 2050, about 50 per cent more than onshore systems. Operation and maintenance costs per kilowatt-hour for offshore wind projects are also up to three times higher than for onshore installations. However, higher capital and operating costs are generally offset by the higher capacity factors that can be achieved in strong offshore wind regimes. Offshore wind at $3/watt with a 55 per cent capacity factor (within the achievable range for Canada's strong offshore wind regimes) is competitive with onshore wind at $2/watt and a 30 per cent capacity factor. Offshore wind may also have advantages related to social and environmental impacts.

Capital costs can represent 75 to 80 per cent of total lifetime cost for onshore wind projects, 30 to 50 per cent for offshore installations. There is, however, far less historical data for projecting installation and maintenance costs and technology longevity for offshore projects, so a conservative estimate would place the total cost of offshore wind projects about 50 per cent higher than onshore.[48]

The dollars per kilowatt-hour in the final column of Table 5 are costs, not prices, and they reflect only the costs of producing the electricity. They exclude downstream costs, particularly the cost of transmission infrastructure to deliver the electricity to end users. These costs can be significant for wind energy, and they vary greatly depending on the physical location of the turbine and limitations of the surrounding grid.

Another factor that will affect the overall contribution of wind to the electricity supply is curtailment, the term for non-dispatchable electricity that cannot be used due to limited transmission capacity, or because the electricity cannot be used or stored when it is generated. A certain amount of curtailment will occur in electricity grids with relatively high penetration of non-dispatchable generation, and it is not necessarily uneconomic from a system perspective. In some system configurations, it may be more economical to ensure that transmission capacity is fully utilized, even if it means that wind generation is occasionally curtailed. This scenario underscores the reality that the capital, operating, and associated unit costs of renewable electricity generation do not by themselves indicate the optimum or cost-effective role for wind or any other low-carbon energy source: That determination requires an integrated analysis of the entire system that takes into account the dynamics and interactions of the various demand, supply, storage, and transmission and distribution technologies and capacities that are available at any given time.

The potential synergies between the variability and intermittency of wind generation and the availability of large-scale storage at hydro dams is a good illustration of the importance of these dynamics. The Canadian Academy of Engineering[49] contrasted the variability and uncertainty of natural energy flows of hydro and wind energy, concluding that:

> A big difference between hydro and wind is that hydro generation capacity is typically associated with storage capacity in reservoirs. The existence of a reservoir allows hydro to be dispatched to match rapid fluctuations in demand better than all other sources of generation …
>
> Two broad approaches have been taken to mitigate the variation. One is to improve forecasting of wind speed and electricity generation at the site of each wind farm. This helps considerably with short-term dispatch. The second approach involves linking wind farms over a broader geographic area. When the wind is low at one site it may be high at another.

The IPCC[51] pointed to integration between hydropower and wind generation as an option for addressing the intermittency of wind resources. "In Denmark, for example, the high level of variable wind energy (>20 per cent of annual energy demand) is managed in part through strong interconnections (1 GW) to Norway, which has substantial hydropower storage. More interconnectors to Europe may further support increasing the share of wind power in Denmark and Germany." The IPCC also stressed the importance of expanded network infrastructure, observing that "strengthening connections within an electrical power system and introducing additional interconnections to other systems can directly mitigate the impact of variable and uncertain RE [renewable energy] sources." The irony for Canada is that, while the prospect for these interconnections is most obvious in hydro-rich provinces like Quebec, the potential carbon reduction of wind is greatest in more heavily fossil-dependent provinces like Alberta. For this and other reasons, the emergence of an interconnected national grid as envisaged by the Canada Power Grid Task Force of the Canadian Academy of Engineering[51] could be an important element of a future low-carbon energy system.

A variety of health and environmental concerns have arisen over the years as the size and height of wind turbines and the land use requirements of commercial wind farms have increased. Issues such as noise, electromagnetic interference, airplane flight paths, loss of natural habitat, property values, aesthetics, and bird and bat fatalities are well understood, and practical steps have been taken to address them. Opponents of wind farms in Ontario have recently claimed that offshore wind turbine projects in the Great Lakes region would adversely affect human health. Scientific studies to date have found no evidence of health

impacts from wind power projects.[52] In July 2012, Health Canada announced a two-year, \$1.8-million study of the potential health impact of wind turbine noise.[53]

Table 6. An Inventory of Low-Carbon Energy for Canada: Wind in 2050

Potential	150 TWh, based primarily on limits to grid integration. The resource is very large compared to the level of electricity or total energy use in Canada. Deployment by 2050 will be constrained by system integration considerations related to variability, transmission capacity, and storage.
Principal Technology Options	Onshore and offshore turbines
Technical Limitations	Major expansion will depend on refurbished grid infrastructure For some sites, distance from source of power to end use
Cost Factors	Onshore capital costs about \$2/watt; offshore about \$3/watt by 2035. Capacity factors from 30-50% for onshore projects, higher for offshore. System integration costs are all-important.
Environmental/ Social Factors	Size and height of turbines Land use for large commercial wind farms Noise and electromagnetic interference Wildlife habitat and bird/bat kills Homeowner concerns about property value, visual landscape, human health

Hydropower

Hydropower is generally divided into two categories:

- Large-scale hydro installations greater than about 50 MW capacity, usually featuring significant energy storage provided by large water reservoirs
- Small-scale, "run-of-the-river" systems with capacity of less than 50 MW and limited energy storage.

Hydropower accounted for about 57 per cent of Canada's electricity production in 2007,[54] and total installed capacity of 75,095 MW generated 347.8 TWh in 2010.[55, 56] Large hydro made up the dominant share of hydropower capacity and production, with only 980 MW and 4,860 GWh coming from small hydro in 2008.[57]

LARGE-SCALE HYDRO[58]

The Canadian Hydropower Association (CHA) estimates that Canada has technical potential for 163,000 MW of new large hydro capacity, in addition to the more than 74,000 MW already installed.[59] Large hydro developments are not generally constrained by technical or economic factors or by long transmission distances, but by environmental and social considerations and public acceptance. Citing Statistics Canada for current generation and the CHA for potential, the Canadian Academy of Engineering[60] summarized the existing and potential resource in the following table:

Table 7. Large Hydroelectric Capacity in Canada

	MW	
Province/Territory	Present	Untapped Potential
Alberta	909	11,775
British Columbia	12,609	33,137
Manitoba	5,029	8,785
New Brunswick	923	614
Newfoundland & Labrador	6,796	8,540
Northwest Territories	25	11,524
Nova Scotia	404	8,499
Nunavut	0	4,307
Ontario	8,350	10,270
Prince Edward Island	0	3
Quebec	37,459	44,100
Saskatchewan	855	3,955
Yukon	78	17,664
Canada	**73,437**	**163,173**

According to Sigvaldason:[61]

> The three decades from 1960 to 1990 saw a very ambitious global program of developing dams and water-related projects, including major hydro developments. Much of this expansion was strongly supported by international financing agencies, led by the World Bank.
>
> Beginning in the 1980s and increasingly in the 1990s, a growing backlash developed against dams and water projects. It was apparent that many of these developments had been implemented without adequate consideration of environmental and social impacts. There were questions about the economic viability of some of the developments, and about lack of attention to social equity and equitable distribution of benefits from hydro development.

The same period saw a growing global backlash against infrastructure projects in general, leading the World Bank to announce in the early 1990s that it would shift its lending away from physical infrastructure in favour of "soft" areas, such as gender equality, good governance, rural development, health care, and education. In 1997, the World Bank and the World Conservation Union (IUCN) established the World Commission on Dams (WCD) to address the environmental, social, and economic impacts of dams and recommend improved planning and development processes for dams and related water projects.

According to Sigvaldason:[62]

> The study began at a time when climate change was only beginning to surface as a major global issue, so the Commission's 2000 report[63] did not include any in-depth consideration of the global potential of hydro to reduce greenhouse gas emissions. However, beginning in the early 2000s, bilateral and multilateral institutions returned to the view that effective economic development must include well-planned, functioning physical infrastructure. Meanwhile, over the last five to 10 years, there has been renewed global interest in hydro as an option for reducing production of greenhouse gases.
>
> The electricity supply systems in Quebec, Manitoba, and British Columbia produce the lowest cost electricity for both industrial and residential/commercial consumers, not only in Canada, but across North America. While hydroelectric developments are capital intensive, their operating costs are very low, and they continue to operate long after they have been fully paid for. There are hydro projects still in operation after more than 100 years of service, and very few major hydro projects, if any, have ever been taken out of operation – or, even after many decades of operation, even considered for removal or demolition.

Depending on hydrology, many hydro facilities can easily operate as either base load or mid- or peaking cycle facilities, and are ideally suited for load following, spinning reserve, system stability, standby, and emergency reserve roles.

Approximately 17,000 MW of capacity is currently in development or under consideration, including Site C in British Columbia, Conawapa in Manitoba, Slave River in Alberta, Petit Mécatina in Quebec, and the Lower Churchill project in Labrador. According to the World Energy Council's energy resource survey, most of the 2,397 MW of capacity now under construction consists of upgrades and refurbishment to existing dams.[64] However, the federal government has sought to support major hydro development by changing environmental review processes and providing financing guarantees.

The WCD Report stated that the construction of large dams and associated flooding of large tracts of land is a much greater concern today than it has been in the past. But industry proponents say Canada is in a unique situation, with potential to increase hydro capacity with limited major reservoir development. According to Sigvaldason,[65] much of the regulation for future hydro developments has already been built, so that the main opportunity is to capitalize on existing regulation:

- In Newfoundland and Labrador, the Lower Churchill Development (Muskrat Falls and Gull Island) could provide 3,074 MW of additional capacity and 16.7 TWh of additional energy from the existing Smallwood Reservoir, the second-largest built reservoir in the world.
- In Manitoba, regulation of the Lower Nelson River is provided by existing control works at the outlet of Lake Winnipeg, and the development of six new generating stations would add 4,100 MW to the 3,886 MW and 23.3 TWh already in place.
- The Peace/Slave/Mackenzie river system has potential to develop roughly 12,000 MW of new hydro generation, in addition to Site C, using regulation of the existing Williston Reservoir, with additional regulation (using control works similar to Lake Winnipeg) to harness potential from Lake Athabasca, Great Slave Lake, and Great Bear Lake.

This existing and potential regulation would add value without resulting in additional flooding. Hydro can also complement the operation of thermal power systems in neighbouring jurisdictions by exchanging relatively low marginal cost off-peak thermal energy (typically night-time operation) with high-value peaking power production.

The WEC calculated that Canada has 90,000 MW of technically achievable hydropower potential and 61,000 MW of economically achievable potential, based on estimates of electricity prices as well as capital, transmission, environmental, and land use costs. Changing prices and policies could increase the range of economically feasible projects by 2050. For example, a price on carbon would improve the economic feasibility of hydropower relative to competing coal- and natural gas-fired generation.

Large hydro's key technical advantage is that it can generate electricity on demand. Using reservoirs for energy storage, large hydroelectric facilities can be incorporated into the existing electricity system relatively easily. They can also produce significant amounts of electricity with only limited GHG emissions due to their scale. In light of these advantages, as noted earlier in this report, hydro reservoirs have been identified as a potential low-carbon storage option in an increasingly distributed renewable system.

The construction costs of large hydro facilities are typically in the billions of dollars, and historically Canada's large hydroelectric potential has been developed with public financing or underwriting. For some governments, the costs are too high to contemplate without joint financing agreements with other levels of

government or long-term electricity purchase agreements with other jurisdictions, so that new supply is often brought onstream as an export revenue generator rather than a contributor to a province's electricity supply mix.

The cost of a large hydro facility can escalate quickly, and suitable locations for hydroelectric power are generally in remote areas, leading to technical constraints and higher costs in transmitting energy over long distances. Table 8 shows estimated costs for three sites currently under review for development: Site C in British Columbia, Romaine River in Quebec, and Lower Churchill Falls in Labrador.

Table 8. **Cost Estimates for Three Large Hydroelectric Sites**

	Site C		Romaine River		Lower Churchill	
Capacity (MW)	900		1550		2800	
Annual Delivered energy (GWh)	4.6		8		16.7	
Period	2004	2011	Initial	Revised	2005	2009
Cost estimates ($ billions)[66]	5.0	7.9[67]	6.5	7.7[68]	4.3[69]	13.4[70]
Transmission	0.09[71]		0.99		3.4[72]	
Unit Cost ($millions/MW)	5.5	7.3	4.4	5.2	2.8	4.8
Transmission as a Percentage of Total Cost	1%		12%		25%	

Much of this cost has to do with the new transmission infrastructure required to connect generating stations in often remote locations to demand centres and export markets. Transmission costs are project-specific due to geography, distance, and existing interconnect infrastructure. As a proportion of total project cost, they range from one per cent at Site C, where transmission is located close to existing infrastructure, to 25 per cent at Lower Churchill, which would entail costly undersea transmission cables and long interconnect distances.

Because of the significant terrestrial impacts on communities and the local environment, large hydro sites have long planning, permitting, and construction timelines. The total time from initial plan to final commissioning can be from five to 15 years, and the various planning stages sometimes take decades.

The hydro sector does not see financing of major developments as a significant issue. Major hydro projects have been successfully financed in Canada for the past 90 years, and there is no shortage of capital for such developments. The investment community's concern focuses on the uncertainty of the environmental review and approval process, which has led some projects to be abandoned after major investments in planning and design.

Electricity production from large hydro facilities may be vulnerable to changes in precipitation patterns due to climate change, and large hydro reservoirs do generate relatively small greenhouse gas emissions. Decomposition of organic matter in reservoirs can lead to releases of carbon dioxide (CO_2) and methane, a greenhouse gas 21 times more potent than CO_2. In 2007, Canada's hydroelectric reservoirs released an estimated 1.66 megatonnes of carbon dioxide equivalent.[73]

Hydroelectric reservoirs flood large land surfaces, often with significant impacts on local ecosystems and communities, but impacts are site-specific. Natural habitats located within the reservoir are destroyed by converting land and rivers into lakes, dams can block fish migration routes, and reservoirs can contaminate fish and ecosystems with toxic methylmercury[74] when developers fail to remove organic material from reservoirs before they are flooded.

Large hydroelectric developments may force community resettlement due to flooding and affect Aboriginal communities that rely on watersheds for economic and subsistence purposes. Hydroelectric development can also open up corridors to areas that were previously less accessible, placing additional strain on Aboriginal and other rural communities due to encroachment.

Although evaporative water losses are a concern in dry regions like southern Alberta, the water actually used in hydroelectric generation is not consumed, and is therefore available downstream for irrigation, drinking water, and recreation. Hydroelectric reservoirs can also be useful to regulate small seasonal variations in water levels, preventing flooding downstream. In its Special Report on Renewable Energy Sources and Climate Change Mitigation,[75] the IPCC added that “a properly designed hydropower project may … be a driving force for socioeconomic development, though a critical question remains about how these benefits are shared.”

Table 9. An Inventory of Low-Carbon Energy for Canada: Large Hydropower in 2050

Potential	163,000 MW, >700 TWh at 50% capacity factor (2,568 PJ)
Principal Technology Options	Large-scale storage dams
Technical Limitations	High capital cost of construction Distance from source of power to end use
Cost Factors	$5,000-$9,000 per kilowatt, including transmission. Projects run into the billions, even tens of billions of dollars in capital investment, typically requiring public or joint public/private financing and risk management, amortized over decades.
Environmental/ Social Factors	Multiple, significant impacts on local environments and communities Long lead times for approval, development, and construction Vulnerability to changes in precipitation due to climate change

SMALL AND LOW-HEAD HYDRO

Small hydro commonly refers to hydroelectric facilities that generate electricity using "run-of-river" (ROR) systems[76] that require little or no water storage in reservoirs, minimize upstream and downstream disturbances to the social and natural environments, and produce zero greenhouse gas emissions during electricity production. Natural Resources Canada defines three categories of small hydro: micro hydro (less than 100 kW, enough to supply the electricity needs of a small factory), mini hydro (100 kW to 1 MW, enough to supply a few houses), and small hydro (1 MW to 50 MW).[77,78]

In 2006, Canada had about 3,400 MW of developed small hydro at 359 sites. According to the World Energy Council, small hydro under 10 MW generated an estimated 4,860 GWh in Canada in 2008.[79] NRCan estimated that Canada has total small hydro potential of 14,270 MW.[80] However, although Statistics Canada projects new small hydro capacity growing at a rate of 50 to 150 MW per year,[81] a study commissioned by NRCan concluded that virtually all the hydro sites that are economically and geographically suitable have been developed.[82] The wide variance in these estimates shows the extent to which assessments of useable renewable energy sources depend on subjective views of whether a development is practically feasible, economically viable, and socially acceptable, as opposed to the raw volume that is physically available and technologically attainable.

Low-head hydro generally describes a hydro unit with a fall of water between 1.5-5.0 metres, although in some jurisdictions, such as British Columbia, a fall of up to 15 metres is considered low-head. NRCan estimates Canada's low-head hydro potential at about 20,000 MW.[83] Refurbishment of more than 600 existing small hydro facilities could also increase their overall capacity by about 1000 MW.[84]

Several demonstration projects are currently testing the potential of in-stream hydro technologies in British Columbia, Quebec, Ontario, and Manitoba.

Typical capital costs for small hydro range from $3,000 to $5,000 per installed kilowatt, for an overall cost of $0.04 to $0.10 per kilowatt-hour for delivered electricity. Capital costs can exceed $6,000 per installed kilowatt for remote projects, with the highest costs attributed to smaller projects on remote sites.[85] Operating costs are generally significantly lower than conventional energy sources, and a small hydro plant can have a lifespan of more than 70 years.

Because most small hydropower facilities do not use large reservoirs, their impacts are much smaller than large hydro developments, but whether their impacts are smaller on a per-kilowatt basis is not clear. Small hydro development disturbs land by requiring access roads, potential forest cuts for transmission lines, and disturbances due to facility construction. Small hydro operations can also have an impact on river hydrology, fish populations, and other wildlife.

With no reservoirs, run-of-river hydro is considered a variable electricity source like solar and wind. Electricity production is a function of water volumes that vary by year, season, and precipitation levels. Although run-of-river flows are more predictable than other intermittent renewables, enabling small hydro sites to provide more firm power to the grid, run-of-river cannot match the ability of large hydropower to supply power on demand. This means the trade-off between large and small hydro is not solely a matter of scale.

Small hydro developments may also disrupt nearby First Nations and rural communities. Protocols for engaging these communities vary by community and province. Since significant small hydropower resources are located on Crown lands that have traditionally been used and claimed by First Nations communities, development of these resources will have to coincide with Aboriginal interests. First Nations have recognized the potential of these projects for community economic development.[86]

Table 10. An Inventory of Low-Carbon Energy for Canada: Small and Low-Head Hydro in 2050

Potential	14,270 MW small hydro, 20,000 MW low-head, 1,000 MW new capacity through refurbishments, for total estimated 185 TWh at seasonal capacity factors of 40-80% (presumed average of 60%), 667 PJ
Principal Technology Options	Run-of-river turbines
Limitations	Not dispatchable
Cost Factors	$3,000-$5,000 per installed kW, $6,000 or more in remote settings, but capacity factors are relatively high.
Environmental/ Social Factors	Requirement for access roads, possible forest cuts, and other disturbances during construction Operational impacts on river hydrology, fish populations, and other wildlife Potential social impacts in nearby communities

Nuclear

The potential contribution of nuclear energy to Canada's low-carbon energy supply in 2050 is not constrained by any practical limitations on the country's uranium reserves or other physical factors, but rather by the contribution that would be practically feasible, economically viable, and socially acceptable.

Canada's large supply of uranium, and the high proportion of that supply that is currently mined for export, suggest there should be little difficulty fuelling an increase in nuclear generation with domestic reserves if nuclear were a significant part of a low-carbon energy future. The country currently has known uranium resources of 572,000 tonnes of uranium oxide (U_3O_8), or “yellowcake”, and exploration continues. In 2011, the World Nuclear Association (WNA) placed annual output at 11,997 tonnes in 2009 and 11,540 tonnes in 2010, the large majority of it for export.[87]

According to the WNA, Canada accounts for about 22 per cent of the world’s uranium output, and was the largest producer until it was overtaken by Kazakhstan in 2009. The McArthur River mine in northern Saskatchewan is the largest in the world, and Canada’s production is expected to increase significantly if and when the new Cigar Lake mine comes into operation.

The development of Canada’s nuclear design and engineering capacity began in the years following the Second World War and peaked in the 1980s and early 1990s, with the last new nuclear power plant in Canada (Darlington) coming online in 1993. Two new reactors are now planned for the Darlington site, and there has been consideration of a second reactor at New Brunswick’s Point Lepreau site in the future, though that possibility is not currently being actively pursued. Still, any consideration of the role nuclear energy could play in meeting Canada’s energy needs in 2050 must take into account the engineering design and construction capacity required to build and operate the plants, how quickly that capacity could be built up, and to what level.

In December 2009, Canada’s nuclear generation capacity consisted of 18 reactors (down from a peak of 22 large power reactors in 1994) in Ontario, Québec, and New Brunswick with total installed capacity of 13,379 MW, and Ontario derived 55.2 per cent of its electricity from nuclear generation. In 2010, the Canadian Nuclear Association estimated the system’s lifetime capacity factor at 76.8 per cent.[88]

In its latest energy supply and demand projection,[89] the National Energy Board anticipated that annual nuclear generation in Canada would increase marginally, from 82 to 83 TWh, between 2010 and 2035. Up to 200 TWh or 720 PJ would be technically feasible by 2050 at output of 7 TWh/year per 1,000-MW reactor.

The only Canadian province currently planning to increase its nuclear capacity is Ontario, with plans for 10,000 MW in refurbishments to existing facilities and 2,000 MW of new construction. In 2010, Ontario’s Long-Term Energy Plan[90] anticipated that nuclear would supply 46 per cent of the province’s electricity in 2030, a modest reduction from 52 per cent in 2010. “Nuclear generation is ideally suited for providing base load generation because of its unique economic and operating characteristics,” the plan stated, and a generation mix of 50 per cent nuclear plus hydroelectric generation will be sufficient to meet most of the province’s base load requirements.

However, this observation also defined the limit to the province’s interest in new nuclear generation. “If nuclear capacity beyond this were added, the hours in the year in which nuclear capability exceeded Ontario demand could substantially increase. Under such surplus conditions, some nuclear units might need to be shut down or operate differently than intended. This could lead to significant system and operating challenges and so, therefore, generating too much nuclear is undesirable." [91]

Although nuclear generation is not a part of other provinces' future capacity planning, there has been some interest in using nuclear facilities to generate process heat for oil sands operations in Alberta. If hydrogen were developed as a major energy currency, nuclear power plants could be occupied in off-peak hours in the electrolytic generation of hydrogen, but difficult and perhaps insurmountable barriers stand in the way of the widespread deployment of hydrogen as a transportation fuel.[92]

In the longer term, there is no fundamental technological barrier to a renewed role for nuclear energy in Canada's energy supply mix. The limits will be defined by economics and social acceptability, and more critical analysts raise questions about:

- The inability of nuclear installations to withstand serious earthquakes and tsunamis
- Chronic technical difficulties that have led to time and cost overruns with plant refurbishments
- The decade-long construction period required before a nuclear investment begins generating electricity
- The inability, reflected in the Ontario Long-Term Energy Plan, to adjust a nuclear plant's output to reflect shifting demand in an integrated grid
- The challenge of safe, long-term disposal of radioactive waste.

Within this cluster of issues, the future cost of nuclear electricity is difficult to predict. Unlike most low-carbon energy technologies, for which costs decline as designs evolve and experience is gained, the cost of nuclear energy has trended upward over time. This could reflect the lack of new plant construction in recent decades, which has limited economies of scale and deployment of new designs.

Atomic Energy of Canada Ltd., the Crown corporation that was sold to Montréal-based engineering firm SNC-Lavalin in 2011, invested heavily in two new reactor designs, one of which is still in development. The Enhanced CANDU 6TM (EC6) is a 700-MW, heavy water-moderated and -cooled reactor that AECL presented as an evolution of its previous CANDU design, the Qinshan CANDU 6 facility in China. The Advanced CANDU Reactor (ACR-1000) is a 1,200-MW, Generation III+ design that uses lightly enriched uranium (LEU) and light water cooling. The ACR-1000 was widely seen as a unique, hybrid design that would help assure the future of the Canadian nuclear industry, but its development was suspended by AECL prior to the SNC-Lavalin sale.[93] The company's website currently states that ACR-1000

development "has been completed to the point that the design is ready for bidding or for discussion with interested utilities."[94] Canadian utility buyers would also have access to a wide range of reactor designs from international suppliers such as Westinghouse, GE-Hitachi, Babcock & Wilcox, Areva, and Gen4 Energy.

In recent years, reactor designs have been trending smaller, taking advantage of modular approaches to manufacturing and assembly, in the hope of reducing capital costs and simplifying maintenance. A number of these small modular reactor (SMR) designs are now available commercially, and at least one is in pre-licencing design review with Canadian regulators. Smaller reactors may open up a wider range of possible applications for nuclear power, and could reduce the need to build new transmission grid infrastructure.

Nuclear generation was one of the low-carbon electricity options included in the report of the Canadian Academy of Engineering's Canada Power Grid Task Force.[95] Although nuclear was seen to be "experiencing something of a rebirth world-wide," the report observed that

> this nuclear renaissance is full of uncertainties, including about the full costs of generating power. To the uncertainties and risks must be added the relatively large size of individual plants, both in terms of MW installed and the investment required. Risks and lumpy size combine to make it hard to finance new nuclear capacity.

The Task Force report suggested a strategy of "parceling and diversification" to spread the costs and risks of a nuclear development across multiple investors, and pointed to a trend toward clustering of nuclear generation units at a smaller number of larger sites.

Beyond financial uncertainties and siting issues, the level of health, safety, and environmental risk associated with nuclear technology has been a matter of sustained controversy over a period of decades, with nuclear proponents and opponents assembling dramatically divergent facts and evidence in either direction. There is also the question of the sustainability of the nuclear option. While this report focuses on low-carbon energy sources, and nuclear is without question one of those sources, the terms of reference of the Trottier Energy Futures Project specify the identification of energy futures for Canada that are both low-carbon and sustainable. As applied to energy systems, sustainability often includes criteria that the technology of traditional, large nuclear plants (which is now, for the most part, decades old) has difficulty satisfying, such as maximum reliance on renewable sources of primary energy and minimum production of long-lived hazardous waste. Advanced generations of reactor design – notably Generation IV systems that are expected to reach deployment around 2025-2030 – could come closer to satisfying these criteria, particularly by changing the fuel cycle to reduce and recycle the spent fuel.

Table 11. An Inventory of Low-Carbon Energy for Canada: Nuclear Generation in 2050

Output Available by 2050	*Minimum* 83 TWh, 299 PJ based on NEB, up to 200 TWh/720 PJ technically feasible at output of 7 TWh/year per 1000-MW reactor
Principal Technology Options	Enhanced CANDU 6 nuclear reactor; Advanced CANDU Reactor Generation III system; Generation IV technology; technologies available from international vendors
Technical Limitations	High construction costs for current technology Not suited for load following operation
Cost Factors	Nuclear costs per kW have increased over time, contrary to the normal trend with technology. Combined with the long hiatus in new nuclear design and construction in Canada, this makes estimates of new nuclear costs difficult and uncertain. Learning curves on new designs and next generation reactors also translate to cost uncertainty. As with other capital-intensive supply, capacity factor and system integration costs are all-important.
Environmental/ Social Factors	Environmental, occupational, and public health impacts at every stage of the nuclear fuel cycle Potential effects of a major reactor accident Risks, viability, and costs of long-term storage of nuclear waste

Bioenergy

The term *bioenergy* refers to all the various ways of using *biomass* feedstocks to deliver heat, electricity and liquid fuels. Biomass feedstocks are a broad category of non-fossil carbon that includes plant materials, algae, manure, waste oils, animal fats, food, and farm wastes that can be burned, gasified, or converted to liquid fuels. The multitude of biomass feedstocks and related pathways to deliver electricity generation and solid, liquid, and gaseous fuels are illustrated in Figure 3. Each feedstock has its own carbon ratio, sustainability issues, and mix of pathways to produce fuels and electricity, making bioenergy the most complex and multi-faceted of the low-carbon energy sources.

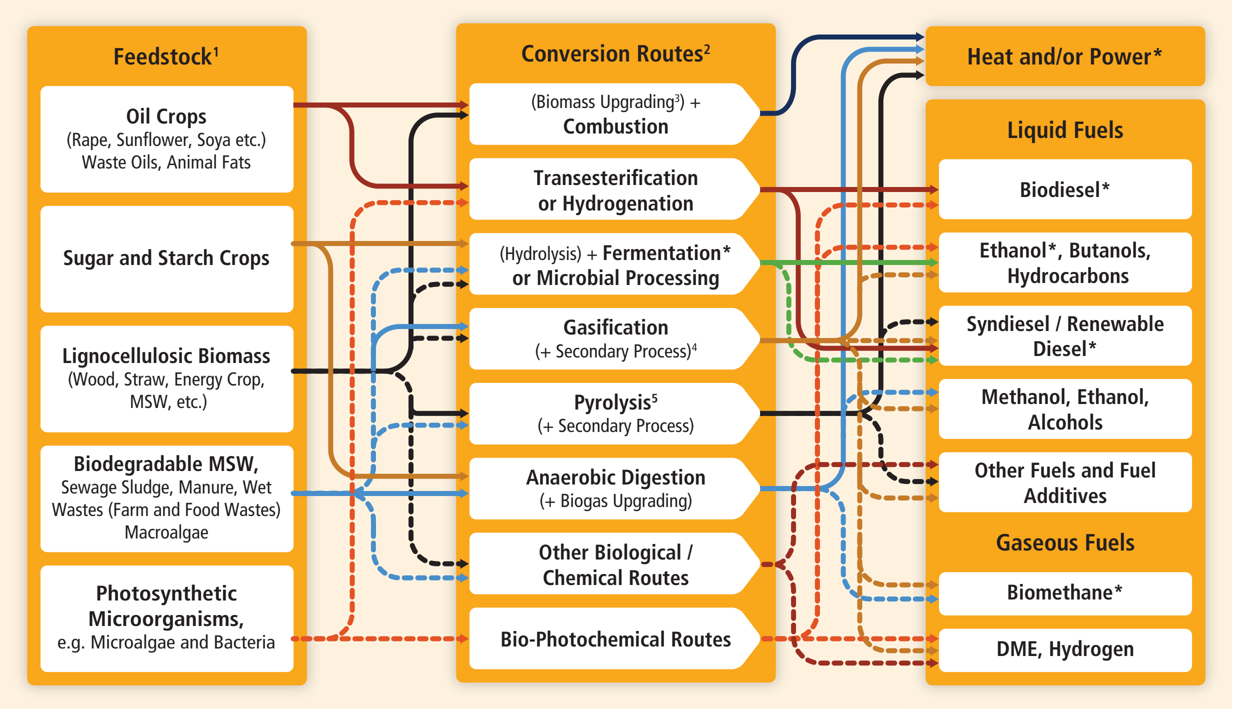


Figure 3. Bioenergy Feedstocks and Conversion Pathways[96]

SUSTAINABLE, LOW-CARBON BIOENERGY FOR CANADA

The technology of bioenergy production and utilization is the focus of intensive research, development, and innovation around the world, as nations and economies seek to supplement or displace fossil fuel use. Low-carbon energy future scenarios almost invariably include an expanded role for bioenergy in a number of forms:

- ***Solid Fuel:*** Modern fuel burning technology is much cleaner and more efficient than in the past, leading to a possible role for solid biomass in power plants, industrial and commercial boilers, and building heating systems. As noted above, an international commodity market for biomass pellets is well established and growing. Current technology and process development efforts, particularly torrefaction, are actively addressing limitations related to energy density, contaminants, and moisture content and absorption during shipping and storage.

- ***Liquid Fuel:*** Mobility is a highly valued energy service and requires energy forms that are dense, storable, portable, and easily distributed. While automobiles and other forms of personal transportation may be increasingly electrified, long-haul freight transport will likely continue to require liquid fuels with high enough energy density to carry heavy loads. Expanded biofuel use in transport is a common theme in most low-carbon scenarios, including all the ultra-low carbon scenarios reviewed by the Trottier Project.[97] On a per-joule basis, liquid fuels for transportation are valued more highly than almost any other form of energy, including electricity.
- ***Biogas:*** Biogenic methane from sewage treatment plants, landfills, and engineered waste treatment facilities is already commercially available and widely used, and farm biogas generators are very common in some countries. Bioenergy development could also include large-scale gasification of wood and other cellulosic feedstocks to produce biomethane and other hydrocarbons. Biogas will be a viable source of low-carbon heat and electricity where the feedstock is plentiful, the end use application is nearby, and biogas generation helps address other issues such as waste disposal or odour management. Canada produces nearly 13 million tonnes of waste per year, the largest volume per capita of the 17 OECD countries,[98] and there is significant potential to generate more biogas from organic waste.

Today, biomass supplies five to six per cent of Canada's domestic primary energy, about half the contribution made by coal, and considerably larger than the share provided by nuclear generation. Pulp and paper mills use the equivalent of about 25 million oven-dry tonnes (Odt) of wood-based energy every year, although it varies with industry production levels. Residential wood burning accounts for another five million Odt. Corn and wheat for the production of ethanol and biodiesel account for less than five million tonnes of agricultural feedstock per year, but volume has been growing rapidly in recent years.

As recently as 1930, biomass still accounted for nearly a third of national energy use, second only to coal, which provided about 50 per cent (Figure 2). At that time, bioenergy was used mainly in the form of wood to provide space and water heating to homes, businesses, and factories. By the end of the Second World War, oil's share of total energy had overtaken biomass fuel. Bioenergy's absolute and percentage contribution to Canada's energy supply continued to decline through the 1960s and 1970s as petroleum, natural gas, and hydropower came to dominate growth in Canada's energy use.

After the oil price shocks of the 1970s, biomass feedstocks enjoyed a resurgence in the pulp and paper industry (wood wastes and spent pulping liquor) and the residential sector (wood burning in modern, high-efficiency stoves and furnaces in some parts of the country). In recent years, there has also been renewed interest and growth in other bioenergy applications, including:

- Electricity generation from municipal solid waste, landfill methane, and wood fuel
- Biogas generation for heat and electricity
- Ethanol and biodiesel production from a variety of sugar- and starch-based crops and animal fats.

CURRENT SOURCES OF BIOENERGY FEEDSTOCKS

Bioenergy feedstocks currently come from three sources: agriculture, forestry, and municipal waste.

Agricultural Feedstocks

Ethanol is the primary biofuel in Canada, and production has been on a steep climb in recent years (Figure 4). By far the largest portion of Canadian ethanol is derived from corn and wheat. With current technologies, one tonne of corn can produce nearly 400 litres of ethanol,[99] while one tonne of wheat can produce approximately 365 litres.[100] In 2009, to produce 1.3 billion litres, ethanol distilleries used 3.2 million tonnes of grain, approximately three per cent of Canada's harvest.[101]

In 2007, the Government of Canada announced a nine-year, $1.5-billion investment to increase the country's biofuel production. Further legislative commitments to the industry came in 2010-2011 with federal and provincial Renewable Fuel Standards (RFS), which require that all liquid fuels in Canada be blended with an average of five per cent renewable fuel for gasoline and two per cent for diesel. Despite this rapid growth, production is still ramping up to meet the 2.0 billion litres of ethanol and 600 million litres of biodiesel mandated by the RFS.

Natural Resources Canada projects production will reach 1.8 billion litres of ethanol and 504 million litres of biodiesel.[102,103]

Between 2006 and 2010, biodiesel production in Canada increased from 43 million to an estimated 190 million litres.[104] This output required 180,000 tonnes of canola oil and animal fat.[105] Natural Resources Canada projects that biodiesel production will reach 500 million litres by the end of 2012, still 100 million litres short of the requirement in the federal and provincial RFS.[106]

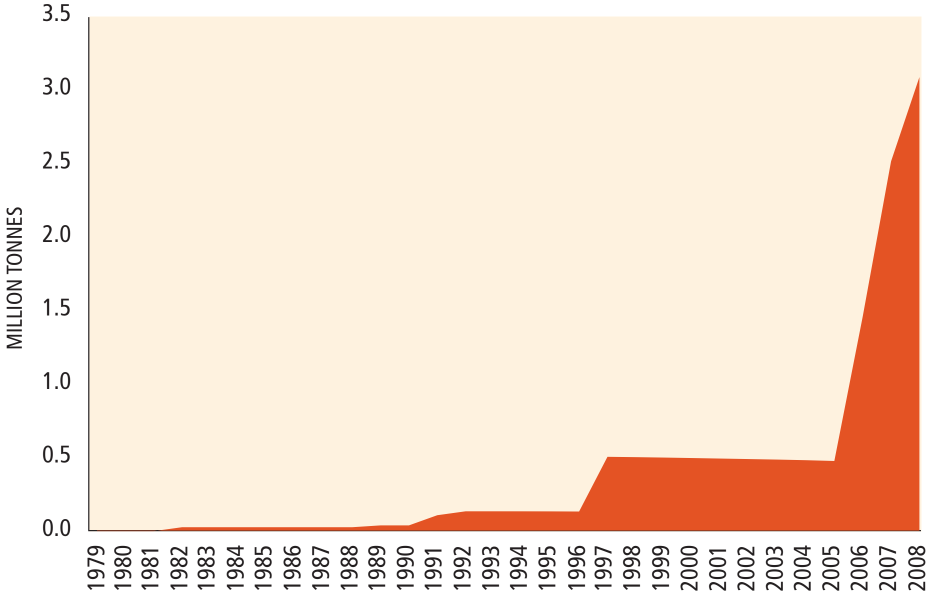


Figure 4: Biomass Use for Biofuels, 1978-2008

The use of food crops for biofuels raises a number of potential social and environmental concerns. Diverting Canadian crops to biofuels may lead to competition for agricultural land, which elsewhere has driven up the price of food and led to trade-offs between food and fuel. The Canadian Renewable Fuels Association states that if all Canadian gasoline contained 10 per cent ethanol, Canada could still remain a major exporter of grain.[107] However, challenges become apparent during drought years, when growing demand for food and expanding biofuel commitments drive up commodity prices. In the summer of 2012, drought decreased corn yields by more than 25 per cent, sending corn futures to record high prices.[108]

A second significant concern is the energy return on investment associated with growing dedicated crops for bioenergy. On a life cycle basis, the estimated energy ratio can vary significantly. For example:

- In 2010, the World Energy Council reported that ethanol from corn delivers only marginally more energy than the fossil fuels consumed in its production, at a ratio of about 1.4:1.[109]
- A more recent and specific study by the United States Department of Agriculture (USDA), placed the ratio as high as 7.75:1 in major corn-growing states.[110]

New crop varieties and agricultural techniques may indeed provide more attractive returns. More broadly, the magnitude of the GHG benefit of using bioenergy of all types depends on which fossil fuel and how much of it is being displaced, and on the choice of process fuel to produce the bioenergy.[111]

Both of these concerns could be relieved if continuing research delivered a viable second-generation biofuel derived from the lignocellulosic biomass of energy crops such as switchgrass, as well as agricultural and forestry biomass. Second-generation biofuels alleviate much of the tension between food and fuel, since they use the crop's leaves, stalks, and other residues rather than the sugars and oils that are required for first-generation biofuel production. Second-generation biofuels also have a more favourable GHG ratio: since the agricultural feedstocks are a byproduct of conventional farming practices, upstream emissions from the cultivation process are already counted as food system emissions. Energy and emissions from the collection and processing of agricultural residues are counted as net emissions, but because the largest share of energy use is in the cultivation of food crops, residues have much lower net emission impacts.

Energy crops such as switchgrasses and cordgrasses usually require less fertilization and tilling than food crops, and can be grown on marginal land. As a result, they produce fewer emissions from cultivation, while limiting competition for prime agricultural land. Land use changes from the production of energy crops, however, could lead to significant increases in GHG emissions. This is especially true if young forests, which have high rates of carbon sequestration, are converted.

Despite their promise, the commercial viability of second-generation biofuels has been limited by the cost of converting cellulose to sugar, and sugar to ethanol. The volume of feedstock can also be limited by physical distance and, more fundamentally, by the need to leave sufficient residues on the ground to allow forests and agricultural lands to regenerate.

Forest Feedstocks

Canada's vast forests house significant bioenergy potential, while raising a different set of social and environmental concerns. Compared to other feedstocks, forest biomass requires relatively small energy inputs per unit of embedded energy,[112] and bioenergy production may be a viable supplementary revenue stream for an industry that is subject to significant swings in global demand for higher-value timber and paper products.

However, different technology pathways vary considerably in the efficiency with which they convert forest biomass into energy, the cost of conversion, and the social and environmental issues that ensue. Combustion of forestry biomass also leads to significant emissions of carbon monoxide and particulate matter, two air pollutants that have impacts on human and ecosystem health for the surrounding region.[113] Second-generation biofuels may introduce a broader range of potential uses for Canada's primary and secondary forest residues, allowing for integration with biorefineries and/or direct cellulose-to-ethanol production.[114]

Canadian pulp mills and sawmills have increasingly used wood waste to power the milling process, or captured the energy for sale. In 2009, Canadian mills used 12 million tonnes of solid wood waste and 17 million tonnes of spent pulping liquor to produce roughly 458 PJ.[115] Nearly 60 per cent of the energy consumption in the pulp and paper industry is now supplied directly by secondary forestry residues produced through the manufacturing process.[116] But the energy potential in this feedstock is entirely dependent on annual harvest volumes that are in turn shaped by wider economic factors: while the industry produced 21.2 million Odt of bark, sawdust, and shavings in 2004, the equivalent of 365 PJ, these mill residues dropped to 14 million Odt in 2009, following the collapse of the U.S. housing market.[117]

Electricity production from biomass is a cornerstone of Ontario's off-coal strategy,[118] and the technology is in use in several other provinces. According to a news report quoting the Canadian Centre for Energy Information,[119] "there were 35 generating stations in Canada fuelled by biomass in 2011, with a total combined installed capacity of 893 MW. Alberta has more than 300 MW of biomass generating capacity, while 9.3 per cent of British Columbia's electricity is produced using sawmill wood waste."

Canada has some very large greenhouse gas sinks, particularly the coastal forests of British Columbia, and climate science includes research on the introduction of new vegetation in marginal regions to sequester carbon dioxide. However, the potential role of forests as a carbon sink falls outside the scope of this report.

Waste to Energy

Using organic wastes as an energy source is an attractive option because of the scale and cost of GHG emissions reduced. While human, livestock, and food waste can provide a somewhat stable feedstock into the future, combustible municipal solid waste – such as paper waste and wood – is likely better directed to recycling and reuse, rather than combustion.[120]

Since the mid-1980s, an increasing number of Canadian landfills have installed gas collection systems that trap the methane released by anaerobic digestion of organic solid waste. Methane is a greenhouse gas with 21 times the warming potential of carbon dioxide, and landfill gas constitutes about 3.5 per cent of Canada's total GHG emissions. In 2009, Canada's 64 landfill gas recovery systems captured just over a quarter of the 27 Mt of CO_2e emissions released from Canadian landfills.[121] Of the 349 kilotonnes of methane captured, half was flared and the other half was used to produce approximately 12.1 PJ.[122] If 100 per cent of landfill emissions were captured and used for energy, landfills could provide approximately 97 PJ, about one per cent of Canada's current primary energy consumption. However, as municipal organic waste diversion increases, the already limited "supply" of landfill gas emissions will decline.

BIOMASS AS A LOW-CARBON ALTERNATIVE TO FOSSIL FUEL?

The carbon dioxide emitted from bioenergy is considered "biogenic," so it is not counted as a net greenhouse gas (GHG) emission. To the extent that the feedstocks and pathways identified in Figure 3 can be developed in Canada in ways that ensure low life cycle emissions of greenhouse gases, bioenergy could play a critical role in achieving a sustainable, low-carbon energy future.

However, while the carbon dioxide emitted when a biofuel is burned is biogenic, the task of harvesting biomass feedstock and converting it to biofuel often requires significant use of fossil fuels, and sometimes fertilizers, through processes that do emit greenhouse gases. Emissions from bioenergy production typically fall into two broad categories:

- Upstream emissions from producing biomass feedstocks and converting them into useful energy commodities
- Emissions from land use changes when soils, forests, or other carbon-sequestering biomes are disturbed.

As noted above, the net GHG benefit of using bioenergy depends in part on which fossil fuel (and how much of it) is being displaced, and on the choice of process fuel to produce the bioenergy. When corn crops are dedicated for energy production, the fertilizer and fuel required to grow, transport, and process the corn result in net emissions that would not otherwise have occurred.

Life cycle GHG emissions from current technologies for producing ethanol from agricultural feedstock in Canada are 40 to 62 per cent lower than gasoline.[123] Bioethanol can also be made from woody (or cellulosic) biomass, and the less GHG-intensive feedstock and conversion technologies could result in life cycle GHG emissions that are up to 75 per cent lower than current agricultural feedstocks and related processes.[124]

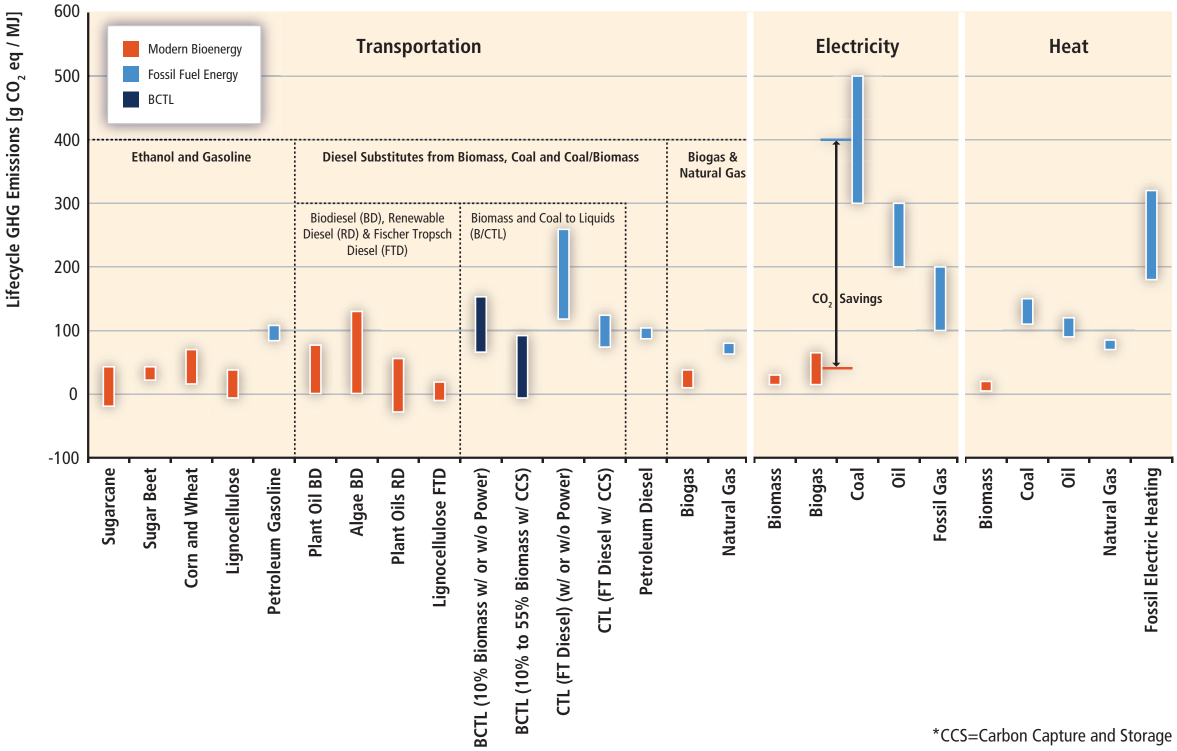
Market demand for biofuels may also shift economic activity to favour biofuel production over other land uses, leading to significant increases in GHG emissions. This risk can be mitigated by appropriate agricultural management practices, such as perennial crop intensification and livestock production on degraded lands.[125]

As noted earlier in this section, agricultural residues for energy production are generally considered less greenhouse gas-intensive than dedicated biomass crops for energy, since any upstream emissions from the cultivation process are already attributed to the food system.

Converting land from young forest with high rates of carbon sequestration to energy crop production shifts the calculation of net atmospheric emissions. Wood burning also leads to significant carbon monoxide and particulate emissions that affect human and ecosystem health for the surrounding region,[126] and black carbon emissions could increase climate effects.[127] Biomass combustion produces lower sulphur dioxide emissions than coal, but higher sulphur dioxide emissions than natural gas.[128]

The IPCC Special Report on Renewable Energy surveyed the research on life cycle greenhouse gas emissions from a variety of biomass-based energy alternatives, and Figure 5, reproduced from that report, illustrates the findings. But even these results do not show the complete picture, since the efficiency of the end use technology can offset the relative emission advantage of one source over another. For example, internal combustion engines convert less than 15 per cent of fuel energy to forward motion, compared to 80 per cent for electric motors. So an electric car powered by electricity generated from biomass has lower emissions than a similar vehicle powered by biomass-based ethanol.[129]

These examples point to the complexity of the transition to a low-carbon future, demonstrating once again that information on the cost and performance of individual supply and demand technologies and options must be complemented by an understanding of wider system dynamics.



*CCS=Carbon Capture and Storage

Figure 5. **Fossil and Bioenergy Life Cycle Greenhouse Gas Emissions Per Unit of Delivered Energy (from IPCC Special Report on Renewable Energy[130])**

HOW BIG COULD BIOENERGY DEMAND GET?

The extent of foreseeable demand for biomass fuels is an important issue, since the sustainable supply of feedstocks may be the factor that limits the role of bioenergy in a low-carbon energy future.

Apart from biomass, most of the low-carbon energy sources considered in this review are options for producing electricity. The Trottier Project's review of low-carbon energy scenarios from eight countries[131] showed that the transition to a low-carbon future will almost certainly involve electrification of such end uses as low-temperature heat and personal transportation. In urban centres, where most passenger transport involves shorter trip lengths, electric vehicles are a viable alternative. But on a 2050 time scale, electricity will not be a practical energy currency for the 40 to 50 per cent of energy end use that will be made up of long-haul trucking, marine and aviation fuels, and various industrial heat processes. Biomass-based liquid and gaseous fuels will have an important role to play in situations where electricity is impractical or cost-prohibitive.

As noted earlier in this section, bioenergy production in Canada has been fairly stable at about 600 PJ, representing five to six per cent of the country's total primary energy supply. For Canada to achieve an 80 per cent reduction in its energy-related greenhouse gas emissions by 2050, the transportation sector must move away from fossil fuels. However, the need for energy-dense fuels will persist, and if that need is met by biofuels, their production will rise significantly, even with much higher vehicle efficiencies.

Figure 6 shows one illustrative scenario of biomass feedstock requirements to provide transportation fuels. In this scenario, the TEFP team projects the demand patterns that will result if automobile fuel efficiency triples and truck fuel efficiency doubles by 2050, and all automobiles are electric by 2040 (with carbon-free electricity supply). Bioethanol and biodiesel both show strong growth until the late 2020s, when accelerating electrification of automobiles triggers a decline in total biofuel requirements. Eventually, continuing economic growth leads to higher biofuel demand, but by 2050 that demand consists mostly of biodiesel for trucks and other freight vehicles. In this scenario, long-haul goods movement requires more than 60 million tonnes of biomass per year by 2050, on top of any ongoing bioenergy requirements for pulp and paper, electricity production, or wood and biogas fuel (currently about 30 million Odt per year). This is only one illustrative scenario; primary biomass requirements could

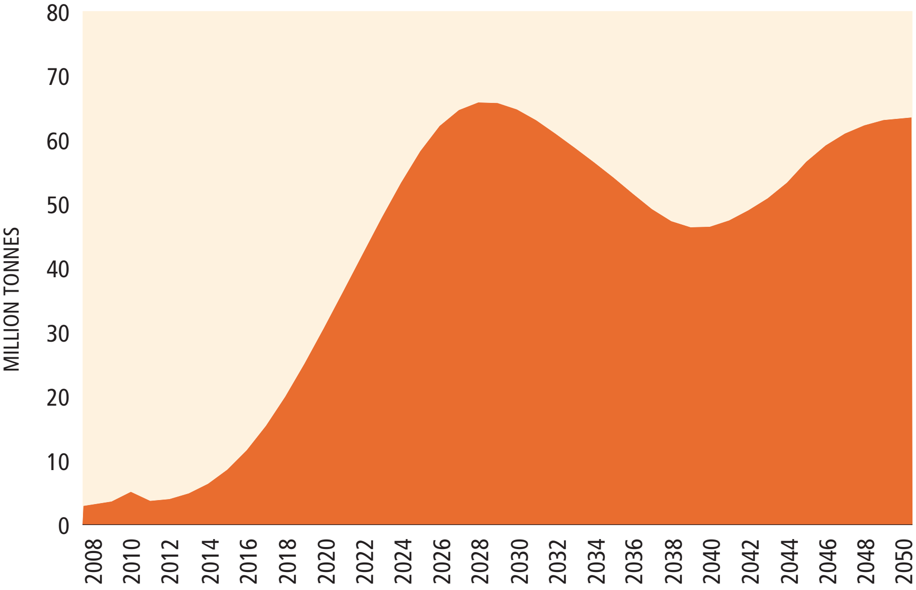


Figure 6. An Illustrative Scenario of Potential Biomass Feedstock Requirements to Provide Transport Fuels in A Low-Carbon Future for Canada

be half as much or twice as much with different assumptions about vehicle efficiency, the extent to which personal vehicles become electrified, and the growth of freight transportation.

This leads us to what may be the most important question about the future of bioenergy use in Canada:

> ***How much biomass feedstock can Canada produce in a manner that is environmentally, economically, and socially sustainable?***

WHAT IS THE SUSTAINABLE LEVEL OF BIOMASS FEEDSTOCK PRODUCTION IN CANADA?

Bioenergy, particularly biofuels, will almost certainly be a central component of any plausible low-carbon energy future. Preliminary analysis by the Trottier Energy Futures Project points toward some scenarios in which biomass use for energy would be three to six times larger than today's levels. So it is crucial to understand how much of the various biomass feedstocks can be grown and produced in a sustainable manner over the long term, and how much of that primary biomass could be available for energy applications.

This is not only, or perhaps even primarily, a technical question. The question of sustainability has environmental, social, and economic dimensions. It involves the farm and forest communities and industries that would be affected by increased reliance on bioenergy. It intersects with all the other products and amenities our forests and farms provide, and it must be answered as part of a larger strategy for restoring and maintaining the health and resilience of our forest and agricultural ecosystems.

Table 12 synthesizes a variety of published estimates of possible production levels for different biomass feedstocks, with these caveats:

- Estimated potential production levels and underlying assumptions vary widely among published sources, and there is considerable uncertainty associated with all the sources. The table calculates total potential output of 7.6 exajoules (EJ) of primary energy from biomass feedstocks, but the data support a range from 3.0 to 12.0 EJ, depending on assumptions about everything from silviculture practices to the impact of insects and forest fires on wood supplies.
- With some exceptions such as annual allowable cut limits, the estimates in the table do not reflect any attempt in the source literature to determine a sustainable level of production. This complex question is the subject of ongoing modeling, analysis, and dialogue within the Trottier Energy Futures Project.
- The table summarizes estimates for Canada's annual primary biomass production potential, not the primary biomass available for energy. Competing uses include food, lumber, pulp and paper, chemical and

pharmaceutical feedstocks, and a myriad of other applications. So this assessment is just a first step in determining a role for biomass-based energy in the Trottier Project's low-carbon energy scenarios for Canada.

Costs for bioenergy depend on both the feedstock and the capital and operating costs of the conversion technology. This high degree of variability makes bioenergy costs a more complex calculation than for solar and wind power, where the "feedstock" (sunshine, wind) is free and the operating and maintenance costs are relatively small. Solid, liquid, and gaseous bioenergy products are already commercial and widely deployed (see Figure 4), at prices that are competitive with fossil fuels, but most current bioenergy products use agricultural, forest, or municipal wastes that are available at little or no cost. In a low-carbon future, the biomass feedstock requirements for energy applications may well be larger than the available supply of such wastes, and lignocellulosic

Table 12. Estimated Annual Primary Biomass Production Potential, Canada

Feedstock	Total Tonnage	Heat of Combustion	Pathways
Food crops: Hay, wheat, corn, barley, canola, corn feed, flaxseed, oats, soybean, beans and peas, rye, mixed grains, other	109 million dried tonnes[132]	1,695 PJ[133]	First-generation biofuels production
Agricultural residues: Stover, husks, silage	70 million recoverable dried tonnes[134]	1,170 PJ[135]	Second-generation biofuels production
Energy crops: Switchgrass, cordgrass on marginal croplands	98 million dried tonnes[136]	1,585 PJ[137]	Second-generation biofuels production
Roundwood	132 million dried tonnes[138]	2,095 PJ[139]	First- and second-generation biofuels; gasification; fuelwood; wood pellets; combined heat and power (CHP); combustion or fossil fuel co-firing to produce electricity
Primary forestry residue[140]	28 million recoverable dried tonnes[141]	440 PJ[142]	First- and second-generation biofuels; gasification; fuelwood; wood pellets; combined heat and power (CHP); combustion or fossil fuel co-firing to produce electricity
Landfill gas	1.4 million tonnes[143]	97 PJ[144]	Direct combustion
Municipal solid waste: Combustible disposed waste	17 million dried tonnes[145]	250 PJ[146]	Direct combustion; thermochemical or biochemical conversion
Municipal solid waste: Combustible diverted waste	6 million dried tonnes[147]	115 PJ[148]	Thermochemical or biochemical conversion
Municipal biowaste	0.63 million dried tonnes[149]	9 PJ[150]	Direct combustion; anaerobic digestion to biogas for heat and electricity
Livestock waste	13 million recoverable dried tonnes[151]	187 PJ[152]	Direct combustion; anaerobic digestion to biogas for heat and electricity
TOTAL PRIMARY ENERGY POTENTIAL		**7,643 PJ**	

sources will grow in importance, along with perennial cropping and integrated agroforestry modes of production designed to satisfy multiple demands on agricultural and forest productivity.

Figure 7 shows cost ranges for delivered bioenergy in various forms, including heat, liquid, and gaseous fuels, and electricity, drawn from the IPCC Special Report on Renewable Energy[153]. Primary biomass feedstock costs vary from zero for wastes to $20/GJ for pellets, and are sensitive to the yield per hectare that can be sustained. Transportation can account for up to 50 per cent of the delivered cost of primary biomass, again reinforcing the importance of productivity per hectare in determining overall costs.

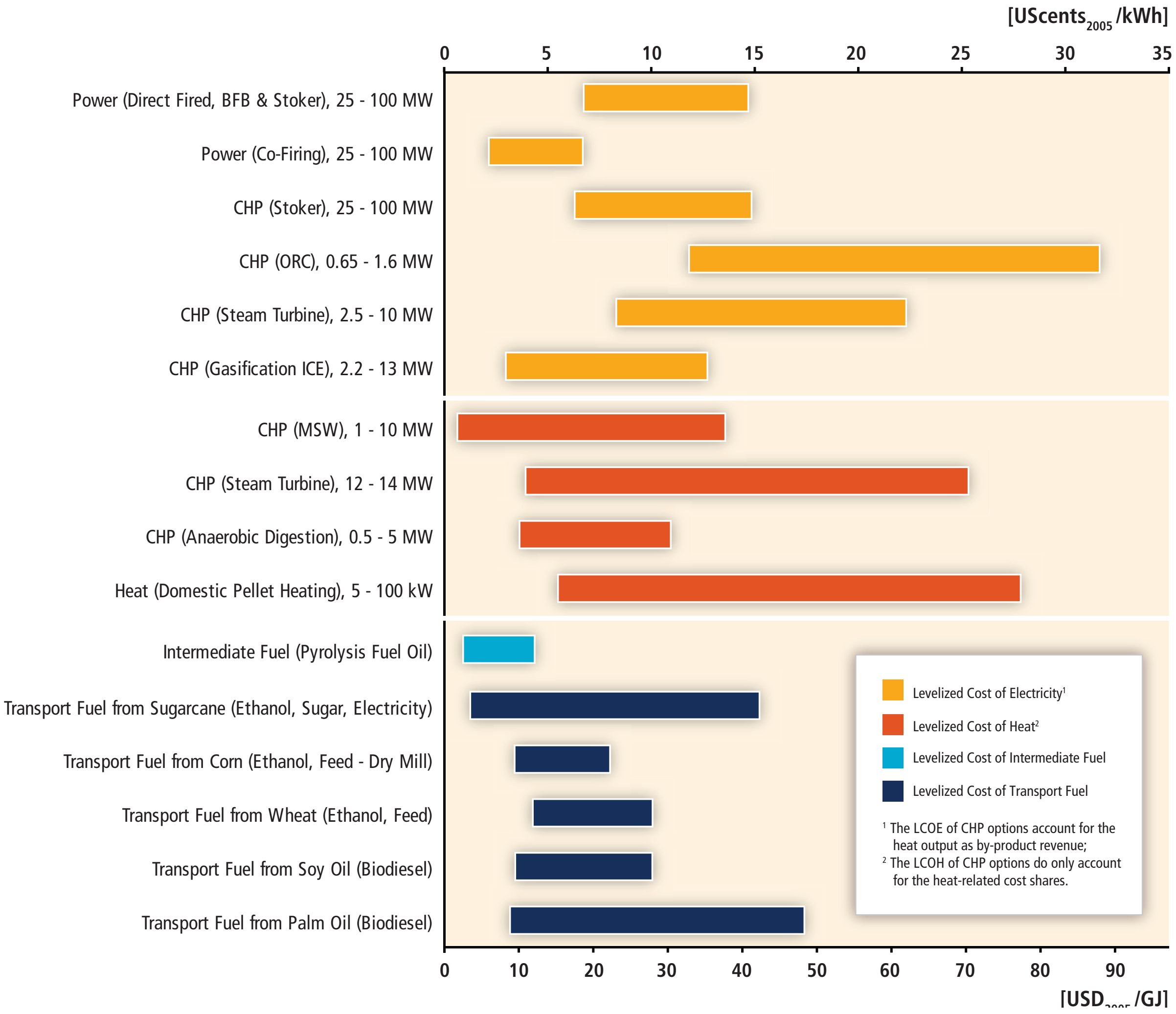


Figure 7. Estimated Bioenergy Costs from Chum, H., et. al, Bioenergy. Levelized costs calculated using 7% discount rate and with technology-specific feedstock costs.
ABBREVIATIONS: BFB: bubbling fluidized bed, ORC: Organic Rankine Cycle, ICE: Internal Combustion Engine.

Table 13. An Inventory of Low-Carbon Energy for Canada: Biomass in 2050

Potential	7,640 PJ (pending availability of feedstocks)
Principal Technology Options	Solid fuel combustion Gasification Liquid fuels Combined heat and power
Technical Limitations	Commercial feasibility of second-generation lignocellulosic production processes
Cost Factors	Variable by site, feedstock, and technology
Environmental/ Social Factors	GHG advantage with first-generation biofuels Potential competition for arable land and crops Limited availability of feedstock after allowing for competing uses and regeneration of forest and agricultural lands

Geothermal

Geothermal energy refers to the heat that radiates from the deep interior of Earth. Three geological factors affect the feasibility of transferring this energy to the surface to drive steam generators or other applications – high-temperature heat, water availability, and rock permeability.[154] There are three broad categories of geothermal technology:

- Hydrothermal, in which relatively shallow, high-temperature geothermal resources in the form of hot water or steam and naturally permeable rocks can be tapped directly for power generation or the provision of heat
- Enhanced geothermal, in which rock fracturing and shearing techniques are employed to gain access to geothermal resources in rocks that are not naturally permeable
- Geoexchange, in which heat pumps take advantage of the relatively constant temperature conditions at shallow depths to provide low-temperature space heating and cooling.

The highest grade of geothermal energy is found near young volcanic zones, at temperatures exceeding 150°C, and is well suited to steam-generated electric power production. Canada has an estimated economically feasible potential of 5,000 MW of electrical power capacity from these high-grade geothermal resources.[155]

Medium-temperature geothermal sources between 50° and 120°C are found in warm sedimentary basins and thermal springs of the Western Canadian Sedimentary Basin of Alberta, northeastern British Columbia, the Yukon, and areas of southern Saskatchewan.[156] Depending on local circumstances, the application most suited to a particular medium-temperature geothermal resource may be electricity production, direct heating, or steam production.

The broad category of geothermal energy includes the use of ground source heat pumps to extract energy from relatively shallow depths. This process is sometimes called geoexchange to distinguish it from the traditional definition of geothermal energy. While ground temperatures fluctuate in the first few metres below the surface, they are fairly constant throughout the year at a depth of about 10 metres, at roughly the annual average surface temperature.[157] This enables electrically powered heat pumps to deliver low-temperature space heating or cooling at a ratio of 2:1 or 3:1 to the electrical energy required to run the pump/refrigerant cycle.

Canada does not have an extensive history of exploiting higher-temperature, conventional geothermal resources for electricity production. However, geothermal is considered a mature, commercially available technology that can be deployed relatively quickly to supply base load power and, in some circumstances, heat and process steam. Constant temperatures over 80°C allow for consistent, commercial-scale electricity production, with capacity factors ranging from 0.7 to 0.95 that make geothermal a reliable renewable energy supply. A geothermal reservoir's productivity declines if it is overused, but the resource can be rested until it recharges. Otherwise, developers must drill new wells to make up for loss of supply and maintain a continuous source of steam. Other challenges with geothermal sites include low conversion efficiencies compared to conventional thermal generating facilities, as well as highly corrosive steam supply sources that necessitate replacement of turbines and piping systems.

In its Energy Pathways report,[158] the Canadian Academy of Engineering concluded that conventional geothermal production could "reduce strain on electricity grids and bring significant reductions in GHGs depending on the fuel being displaced. Work to reduce materials and installation costs would be beneficial."

To date, geothermal resources have been developed where natural rock porosity makes it feasible to proceed. With enhanced or engineered geothermal systems (EGS), high-pressure hydraulic stimulation is used to improve the porosity of rock formations and facilitate the extraction of geothermal energy. Enhanced geothermal opens up significantly more opportunities for electricity production, allowing geothermal installations wherever there is a high thermal gradient without requiring existing reservoirs or porous rock for fluid flows.

The CAE found that enhanced geothermal technology is "not highly developed." While enhanced geothermal could add significantly to the potential energy inventory over the longer time horizon of the TEFP scenarios, its contribution has not been factored into this overview, since known technologies are still primarily in demonstration and are not available commercially.

Geothermal costs depend on the quality of the heat resource and the depth of the well. At 200°C and depths of 2.0 to 3.5 kilometres, the estimated cost is $3,000 per kilowatt of installed capacity, including drilling and plant costs.

However, only 25 per cent of test wells reveal adequate resources for electrical generation, and the cost of drilling the test wells that do not qualify for further development adds another $10,000 per kilowatt to the overall cost of geothermal.[159] Delivered electricity costs can therefore depend largely on the success rate of test drilling operations. Improved well drilling techniques at depths beyond 3.5 kilometres can reduce the cost of geothermal by 13 to 24 per cent, while greater plant efficiency could cut costs by 20 to 30 per cent.[160]

The environmental impacts of geothermal production are generally comparable to or more modest than the effects of other low-carbon technologies. Geothermal requires an order of magnitude less land per unit output than wind. Water used in geothermal production is taken from deep underground aquifers, where they exist, and is fully returned to source through the production process. Greenhouse gas emissions are on the same order of magnitude as hydroelectric reservoirs. Deep wells often emit hydrogen sulphide and other toxic substances that must be strictly controlled and eventually reinjected back into the well. Despite the promise of geothermal production, it remains limited in Canada primarily because of location, access to the grid, and prohibitive exploration and capital costs.

Table 14. An Inventory of Low-Carbon Energy for Canada: Geothermal in 2050

Potential	High temperature: 5,000 MW, 31 TWh, or 110 PJ at 70% capacity factor Enhanced geothermal potential estimated at 50,000 MW[161]
Principal Technology Options	Underground wells (Excludes heat pump/geoexchange systems)
Technical Limitations	High cost and perceived risk of exploration
Cost Factors	For conventional geothermal, $3,000 per kW for high-temperature heat, plus ≥$10,000 per kW for test drilling; produced electricity at $0.035-$0.1/kWh. Enhanced geothermal costs still very uncertain.
Environmental/ Social Factors	Limited by productive resource sites Minimal GHG emissions, on a par with large hydroelectric reservoirs Hydrogen sulphide and other toxics must be carefully controlled in closed-loop system

Wave

The high predictability of wave patterns formed by prevailing winds makes wave energy a potentially reliable energy source. Many technologies have been proposed to harness wave energy, with some of the more promising prototypes undergoing demonstration testing at commercial scales.

The theoretical quantity of wave energy along Canada's east and west coasts is enormous. In 2006, the Canadian Hydraulics Centre estimated the reserve to be 183 GW at depths of up to one kilometre, nearly three times the current output of all the power stations in Canada, with an extractable resource of 27.5 GW from the coasts of British Columbia, Nova Scotia, and Newfoundland and Labrador.[162] However, harsh maritime conditions, conversion losses, and environmental and social factors limit the actual usable power from waves to a small fraction of this potential, with major variations in output by season. The National Roundtable on the Environment and the Economy estimated the total potential of wave energy at between 10,100 and 16,100 MW.[163]

The IPCC[164] placed the investment cost for wave energy technologies between $6,200 and $16,100 per kilowatt (in 2005 dollars). The World Energy Council compared generating costs for initial and mature energy designs and showed that the average value was about $410/MWh, falling to $80-150/MWh for mature designs.[165]

Potential impacts on marine ecosystems include changes to natural coastal processes, disruption of marine habitats, water quality changes, impacts of noise, vibration, and electromagnetic fields on marine organisms, and the interaction of cumulative impacts.[166] The extent of these impacts varies by technology design, project scale and location, and distance from the coast.

Table 15. An Inventory of Low-Carbon Energy for Canada: Wave Energy in 2050

Reserve	Between 10,100 and 16,100 MW; at 25% capacity factor would yield 22 to 35 TWh (79 to 102 PJ)
Principal Technology Options	Below-surface turbines
Technical Limitations	Oscillatory waves that are difficult to harness Harsh coastal environmental conditions Remote sources far from power grid Emerging technology that requires further R&D
Cost Factors	$6,200-$16,100/kW, $80-150/MWh mature; $410/MWh emerging
Environmental/ Social Factors	Potential changes to natural coastal processes, disruption of marine habitats, water quality changes, impacts of noise/vibration/ electromagnetic fields on marine organisms, all depending on technology design, project scale and location, and distance from the coast

Tidal

The kinetic energy embodied in the rise and fall of tidal waters constitutes a large, renewable energy resource in Canada. The 20-MW Annapolis Tidal Station in Nova Scotia went online in 1984 and produces 80 to 100 MWh of electricity per day, depending on the tides.[167] The Annapolis station features a tidal barrage, but the outlook for the future exploitation of tidal energy focuses on the energy contained in tidal currents, the flows of water created in coastal zones by the ebb and flow of the tidal cycles. A variety of "in-stream" turbine technologies are at various stages of development, all designed to extract energy from tidal currents, without the use of dams or barrages and their associated negative environmental impacts.[168]

The theoretical potential of the tidal energy resource is very large, with the best sites for tapping tidal currents located in coastal lagoons, estuaries, and narrow passages between islands. A May, 2006 assessment for the Canadian Hydraulics Centre identified 191 sites with a total mean potential power of 42.2 GW in British Columbia (4.0 GW), Quebec (4.3 GW), Atlantic Canada (3.3 GW), and the Arctic (30.6 GW, mostly in the Hudson Strait). Leaf Basin in Ungava Bay and Minas Basin in the Bay of Fundy are the two highest sources of tidal range in the world, but studies over the years have determined that development would be costlier than competing hydro and thermal options. In recent years, much of the focus in tidal development has shifted from tidal barrages to in-stream developments, mainly to address potential difficulties with public acceptance.

Most of Canada's tidal potential is in areas affected by sea ice, and most of the largest sites are far from the existing electrical power grid, or from the main centres of electricity demand.[169] Extraction is also limited by the need to minimize disturbances to tides and tidal flows. About 15 per cent of the potential, or 6.3 GW, is considered to be extractable. Capacity factors will be site-specific, and the technologies are still in the early stages of development, but assuming a 26 per cent average capacity factor,[170] the 6.3 GW represents an annual energy potential of 14.5 TWh, or 52 PJ.

Tidal energy systems are new enough that estimates of the cost of commercial installations are tentative. The IPCC Special Report on Renewable Energy indicates capital cost of tidal current systems in the range of $5,400-$14,300 per kilowatt, but the estimate is heavily qualified due to the pre-commercial status of the technologies[171] and does not include any investments in transmission that would be required to deliver the energy to population centres.

Table 16. An Inventory of Low-Carbon Energy for Canada: Tidal in 2050

Potential	14.5 TWh, 52 PJ (6300 MW at 26% capacity factor)
Principal Technology Options	Tidal current technology, in-stream turbines
Technical Limitations	80% of potential is located in areas with seasonal ice Much of the potential is far from current power grid Technologies are still under development
Cost Factors	No commercial data; significant cost reductions will be required to achieve a competitive position with other renewable electricity sources.
Environmental/ Social Factors	Tidal barrages cause substantial environmental change and obstruct other maritime activities, but the preferred tidal current technologies are considered relatively benign environmentally.






Conclusion

Canada has vast renewable energy resources in the form of hydropower, solar, wind energy, and biomass, as well as wave, tidal, and geothermal resources that are many times larger than current or projected levels of total fuel and electricity consumption. The country also has uranium resources that are very large relative to domestic requirements. So the prospects for a transition to a "post-petroleum" energy future are not limited by a physical shortage of renewable and carbon-free energy sources.

The technologies for harnessing these resources are at various stages of development and economic feasibility. But they are advancing rapidly and their costs are declining, as the international community intensifies its efforts to find safe, carbon-free alternatives to continued reliance on fossil fuels. Mature technologies for harnessing hydropower are finding new applications, while wind and solar generation have entered the mainstream of the electric power system. The potential for biomass-based solid, liquid, and gaseous fuels is driving intense research and development on an array of new bioenergy technologies, including agricultural and silvicultural innovations for ensuring a sustainable supply of primary biomass.

But Canada's pathway to a low-carbon energy future is not yet completely clear. This review has led to broad conclusions about two different types of constraints to the provision of electricity from renewable and low-carbon sources, and liquid and gaseous fuels from biomass.

Electricity

Canada has an abundance of low-carbon options for producing electricity. The fundamental question is how to capture that potential and apply it sustainably and economically to meet Canadians' energy service needs and wants.

A much larger role for electricity in meeting end use needs, combined with accelerated deployment of carbon-free electricity supplies, is an essential part of the transition to a low-carbon energy system. Realizing this potential, however, will not be primarily a matter of building wind turbines, solar panels, or other carbon-free generation and connecting the new technologies to the existing transmission and distribution system.

The new grid will be more complex, using information technologies to balance a disparate set of supply and demand resources, including dispatchable and non-dispatchable generation, conventional renewable and non-renewable generation, energy storage, inter-grid transfers, responsive demand, and a transmission and distribution infrastructure that supports a high degree of connectivity and multi-directional flows of energy and information. The assurance of an uninterrupted, reliable supply of electricity, and the cost of that reliable electricity, will depend on the cost of the whole system. Community acceptance will almost certainly be a challenge for some technologies in some settings, just as it is for today's higher-carbon energy mix.

The average price of electricity will probably be higher than it is today. Even with breakthroughs in key inputs like the capital cost of photovoltaic electricity, a successful transition to a low-carbon energy system will depend on significant capital investments in storage, transmission infrastructure, complementary renewable sources, and the provision of sufficient, readily available generating capacity to ensure a continuous, reliable electricity supply. The net impact of higher prices on firms and households will be partly offset by investments in efficiency and, in some cases, self-generation, adding to the complexity of grid management.

Liquid and Gaseous Fuels

The challenges are quite different for the supply of liquid and gaseous fuels for transportation and other end uses that cannot feasibly convert to electricity based on technologies that are viable today, or likely to be available for large-scale use by 2050.

For these applications, biomass-based fuels are seen as the preferred low-carbon option, but the sustainable supply of primary biomass feedstock may very well be the limiting factor. The total primary photosynthetic productivity of Canadian forest and agricultural lands is large enough to meet the foreseeable demand, and could be boosted further with new agricultural and silvicultural techniques and technologies, but energy is not the only demand on that biomass or the ecosystems in which it grows. These ecosystems are the basis of the biodiversity that sustains our economies, supplying our food, lumber, paper, recreation, habitat, and a myriad of other uses and commodities, and the imperative to manage them sustainably places a limit on the primary biomass that can be used for energy.

A First Step

This review of low-carbon energy resources is just one contribution to the development of comprehensive, integrated scenarios for a transition to a sustainable, low-carbon energy system. The research shows that Canada has the necessary physical supplies of low-carbon energy, and that the technologies required to harness these critical resources are either available now or in advanced stages of development. They are often more expensive than their fossil fuel counterparts, but their unit energy costs have been declining, they have other valuable attributes (not the least of which is their zero- or low-carbon content), and they are playing a growing role in the energy system. The prospects for a transition to a low-carbon future will depend not so much on the availability of the necessary physical resources, or on the cost and performance of any particular technology, as on the integrative strategies that combine the individual elements in systems that can deliver affordable, reliable, sustainable energy services. This system view is a central focus for the Trottier Energy Futures Project's ongoing scenario development and modeling.

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Notes

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170 The IPCC SRREN includes other types of "ocean energy", including ocean currents, ocean thermal energy conversion (OTEC) and salinity gradients, all of which are in early stages of development and which have not been included in our inventory of low-carbon energy potential in Canada for 2050, Arvizu et. al, *Technical Summary*.

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