Renewable and Sustainable Energy Reviews 78 (2017) 1397–1409

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The role of energy technology innovation in reducing greenhouse gas emissions: A case study of Canada

Sarah M. Jordaan[a,b,*], Elizabeth Romo-Rabago[b], Romaine McLeary[b], Luke Reidy[b], Jamal Nazari[c], Irene M. Herremans[b]

[a] Johns Hopkins University, 1619 Massachusetts Avenue NW, Washington, DC 20036, United States
[b] University of Calgary, 2500 University Drive NW, Calgary, AB, Canada T2N 1N4
[c] Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6

ARTICLE INFO

Keywords:
Energy innovation
Climate policy
Greenhouse gas emissions
International commitments

ABSTRACT

Understanding the influence of energy technology innovation in reducing a country's greenhouse gas emissions requires a systematic review to characterize the existing system. A comprehensive data review of available financing mechanisms and investments by government and industry is undertaken for the case of Canada, coupled with an organized examination of existing international, federal, and regional climate policies that advance innovation. Results indicate that investments from early research and development through to capital expenditures are heavily weighted towards fossil fuels. Though federal efforts to meet international commitments have been unsuccessful, regions implementing high carbon fuel phase-out, renewable portfolio standards, and feed-in-tariffs were found to be successful in reducing emissions. Financing for clean energy projects is readily available; however, there is no complete database available for investors to discover these opportunities. To enhance clean energy innovation in Canada and enable success in emissions reductions, we suggest that investments (from research and development to capital expenditures) and regional policies should be aligned with federal commitments, along with clear communication of available financing to attract clean energy investors. Our approach to a systematic review is broadly applicable to other regions where there is interest in understanding and improving the role of innovation in reducing greenhouse gas emissions, particularly in countries with federalist political systems and large fossil fuel reserves.

1. Introduction

Climate change is one of the most pressing challenges in energy policy due to the increasing risks to human and natural systems predicted by climate science combined with the uncertainty in the magnitude and pace of the overall impacts [1]. As stated by the Intergovernmental Panel on Climate Change (IPCC) [1]: “human influence on the climate system is clear, and anthropogenic emissions of greenhouse gases are the highest in history.” The role of energy technology innovation in reducing emissions is becoming increasingly recognized in the transition to more sustainable, lower carbon energy [2,3]. There have been a number of calls for research to improve the role of innovation and innovation systems in this transition [4–6]. At the same time, it has become a prominent subject in politics and policy, with a recognized need to create demand for clean energy through policy along with strategic investments in research, development, demonstration and deployment (RD3) [2,7]. Climate policy, investments, and financing should be coordinated with careful thought about the role that energy technology innovation can play in reducing emissions.

While there are many confounding factors that influence a region's overall greenhouse gas emissions, we provide one possible perspective that emphasizes the role of innovation. International commitments made through the United Nations Framework Convention on Climate Change (UNFCCC) are consistently not realized in Canada. The country has substantial fossil fuel resources and operates within a federalist political system, making it a useful case for countries with similar socio-political contexts. Previously, Canada committed to reduce its economy-wide greenhouse gas emissions to 17% below 2005 levels by 2020 for the Copenhagen Accord, in alignment with the United States [8]. With the measures applied, Canada's annual emissions are expected to be 727 megatonnes of carbon dioxide equivalent (Mt CO_2 eq) in 2020 [9]. This is 130 Mt CO_2 eq lower than where emissions would have been in 2020 if no measures had been taken; however,

Abbreviations and units: R & D, Research and development; RD & D, Research, development, and demonstration; RD3, Research, development, demonstration and deployment (RD3); ETIS, Energy technology innovation system; ETI, Energy technology innovation; CAPEX, Capital expenditures; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; NEB, National Energy Board; StatsCan, Statistics Canada; Mt, Megatonnes; CO2 eq, Carbon dioxide equivalent

* Corresponding author at: Johns Hopkins University, 1619 Massachusetts Avenue NW, Washington, D.C. 20036, United States.

http://dx.doi.org/10.1016/j.rser.2017.05.162
Received 25 June 2016; Received in revised form 1 March 2017; Accepted 19 May 2017
Available online 27 May 2017
1364-0321/ © 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/BY/4.0/).

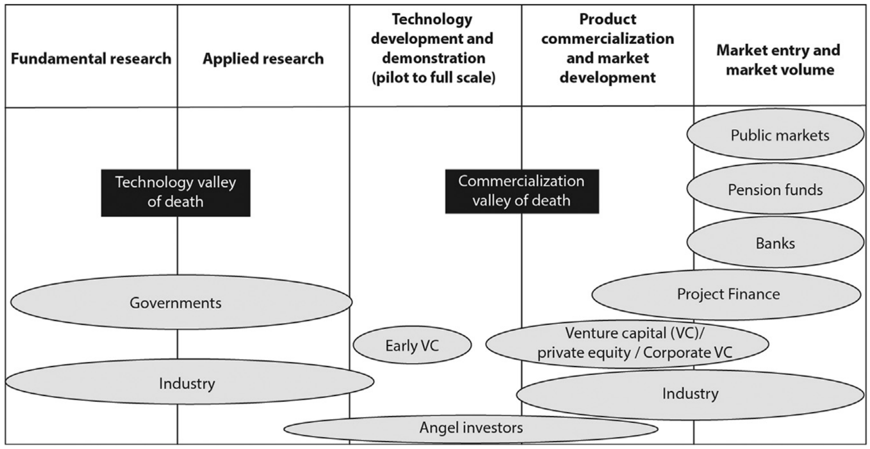

Fig. 1. Illustrative depiction of actors in the innovation system and the funding gaps, also referred to as the Innovation Gaps or Valleys of Death (adapted from [23,24]). Two valleys of death have been noted for clean energy innovation: (1) the technology valley of death that occurs between the first and second stages of technological development (between fundamental and applied research), and (2) the commercialization valley of death that occurs as entrepreneurs attempt to raise capital for demonstration through to the first commercial-scale facility [23].

emissions would not be low enough to meet the commitments made during the Copenhagen Accord. Canada would have yet to reduce another 116 Mt CO_2 eq to meet the target. The latest commitment includes an emission reduction of 30% of 2005 levels by 2030 [10], providing a new window of opportunity to achieve emission reduction goals. The ability of decision-makers to reduce emissions can be improved by energy technology innovation (defined here as the process by which individuals, firms and organizations develop and implement the use of new energy products, designs, processes and methods) [11]. In order to advance clean energy innovation, a comprehensive strategy is required that includes coordination between the public and private sectors [12].

We use Canada as a case study in the development of a systematic review to understand better the role of a country's energy technology innovation in meeting international commitments. The review characterizes Canada's energy technology innovation system relative to overall emissions performance. The current investment portfolio for low-carbon technologies and available financing mechanisms are examined alongside an organized presentation of existing policies to incentivize clean energy innovation. Data were analyzed on government and industry investments in innovation of technologies that have delivered or promise to deliver on greenhouse gas reductions. Available financing mechanisms were compiled from numerous databases. Where data were incomplete, a questionnaire was deployed to the developer of the mechanism to gain a more complete understanding of the available funding. Research has shown that when there are no policies to create a market for clean technologies (or "market pull"), policies and investments to advance technology innovation (or "technology push") have yielded lower returns [13]. Therefore, we compiled existing climate policies at the international, federal, regional, and provincial government levels and categorized them as technology push and market pull. Results from the policy and investment review are discussed relative to actual performance in greenhouse gas emission reductions at each level of government. Generating an understanding of the potential impact of policies and investments relative to greenhouse gas emissions performance can support the development of guidance for national governments in realizing reduction targets and climate goals. Our approach to a systematic review can be applied broadly across governance levels and regions to understand better the improvements that can be made to innovation systems.

2. Energy technology innovation: a systems approach

To capture the complex suite of investments, policies, and actors involved across iterative innovation stages, scholars suggest employing a systems approach [6]. The assessment of an energy technology innovation system (ETIS) can be undertaken quantitatively or qualitatively [6]. In this study, we review both policies and quantitative data on investments and financing in light of their potential correlations with greenhouse gas emissions performance. Previous studies have focused on investments [2,7], the importance of policy design and implementation in achieving clean energy innovation [14–16], specific types of technologies (e.g. tidal [17], PV [18] and wind [18,19], with relatively few focusing on practical applications of ETIS theory (e.g. [20]). Studies have either focused on specific components of ETIS in particular regions or countries (e.g. [2,21]), across countries [19,20], or on the theoretical contribution of ETIS to innovation literature more broadly [6]. While theories of innovation include ETIS [5], the authors have yet to find a systematic review of a country's ETIS discussed relative to GHG emissions performance in a federal political system such as Canada's. To better understand and provide recommendations for improving an innovation system (rather than recommendations specific to a technology, for example), it is important to understand all involved technologies, investments, and the actors [6]. While most available data relates to federal spending in R & D, spending related to demonstration and deployment (having stronger ties to private investment) must also be understood [3,22]. Our review has been developed to improve our understanding of the role of energy technology innovation in supporting a country's reduction of greenhouse gas emissions in light of international agreements. We use Canada as a case study; therefore, the federalist political system necessitates an understanding of federal policy in addition to provincial and territorial policy.

Governments can and often do play a significant role in advancing innovation. For example, the innovation gap (or valley of death) is created by a period of low funding intensity along the innovation process (Fig. 1). The lower funding intensity may be a result of higher capital risk and lower financing due to investor risk aversion. In order to bridge the innovation gaps, the government can implement carbon regulation (e.g. taxes), subsidize research and development (R & D) by private corporations, sponsor graduate fellowships, support university and national laboratory research, offer innovation prizes, and provide funding opportunities to large-scale demonstration projects [25,26]. If not carefully planned and implemented, government activity can also widen the innovation gap [27]. First, if the emphasis is placed on basic research, output from research activities may be inflated when compared to what the private sector is willing to fund in later stages of the innovation sequence. Second, if government funding is concentrated solely on early R & D, less attention may be placed on intermediate-stage activities necessary to bridge the innovation gaps or coordinating research projects across the innovation process. In addition to shifting the concentration of public investment across innovation stages (e.g. more money invested in R & D when compared to commercialization), Murphy and Edwards [28] have proposed three additional strategies for advancing clean energy technologies. First, providing access to data, knowledge and insights should reduce information gaps and asymmetries between both sectors and support sound investment decisions. Such transparency can support the development of policy and investments that reduce the innovation gap for technologies with high potential for both emissions and cost reductions. Second, policy should be developed recognizing that a shift from technology to market may help bridge the innovation gap for the case of these high potential technologies. Finally, new co-investment partnerships should be explored between private and public sectors where potential exists at different stages across the innovation process.

3. Methods

We developed the model in Fig. 2 from the existing literature to shape our systematic review that characterizes the role of energy technology innovation in reducing greenhouse gas emissions. The interactions in an innovation system occur across different levels of governance, from international to national to sub-national, with the latter two tiers emphasized by policies in federalist political systems. Each level of governance will have different but perhaps overlapping sets of actors, networks, and institutions as well as experience with different political, social, and environmental contexts within which the innovation system operates. The focus of our review is on investigating funding across innovation stages, available financing, and policies to promote innovation. Our evaluation provides deeper insight into Canada's status on two of the three aspects of innovation [13]: (1) the status of the current R & D portfolio and (2) the success of implementation and diffusion of new technologies. We do not assess the effectiveness of R & D expenditures in realizing new innovations as this work would require an in depth analysis of patents, which is out of the scope of the present review. In order to understand the current investment portfolio, an analysis of available private and public investment data in clean energy R & D was undertaken. Capital expenditures (CAPEX) are reviewed to quantify successful deployment and diffusion. Finally, a policy review is compared to greenhouse gas emissions performance to discuss qualitative correlations between the overall outcome and extent of policy implementation. More specifically, the policy review includes international, national, and subnational policies. We discuss provincial and territorial emissions performance vis-à-vis a critical examination of expenditures, available financing mechanisms, and policies. Through this evaluation, we identify areas where financing, policy, and data transparency can be improved to support the role of innovation in reducing greenhouse gas emissions and meeting international commitments.

3.1. Review of current investments

For this critical first step, data were compiled on investments in innovation of existing and emerging energy technologies. Data collection included government, non-government and industry investments to capture the range of actors involved in the innovation process in broad categories. Federal investments in energy RD3 from 1974 to 2014 were collected from the International Energy Agency (IEA). Statistics on national research, development, and demonstration (RD & D) budgets collected by the IEA are used by the member states when facing decisions about innovation, such as those related to investments and policies. The IEA statistics are publically available, so research institutes, educational institutions, and private business regularly consult the information. The quality of the statistical data depends directly on the national data collectors in each country. In Canada, data collection is tasked to the National Energy Board (NEB) and Statistics Canada (StatsCan). Industrial investments in energy R & D are also reported by Statistics Canada. Private investment data on CAPEX are not publicly available, so data were compiled from Bloomberg and Clean Energy Canada (2015) [34]. Industry expenditures were compared to government expenditures to understand how Canada's overall investment strategy supports clean energy, an area that has not yet been well investigated in energy innovation research [6].

To account for additional portfolios and programs (e.g. funded by philanthropists and provincial governments), financing mechanisms in Canada were reviewed using public resources. Gaps in data were filled by conducting a survey of institutions. The Decentralized Energy Canada (DEC) database was used to evaluate 193 funding programs and the Grant Connect database was used to identify another 204 grant programs. DEC is a national technology accelerator that has served as Canada's market access hub for the decentralized energy industry. The DEC database was compiled from a comprehensive literature review from subscriptions such as Bloomberg, Capital IQ, Mint Globe, SME Benchmarking tool at the Industry Canada site, Financing and Growth of Small and Medium Enterprises data files and from DEC's subscriptions (e.g. Bloomberg New Energy Finance, Analytica Advisors), as well

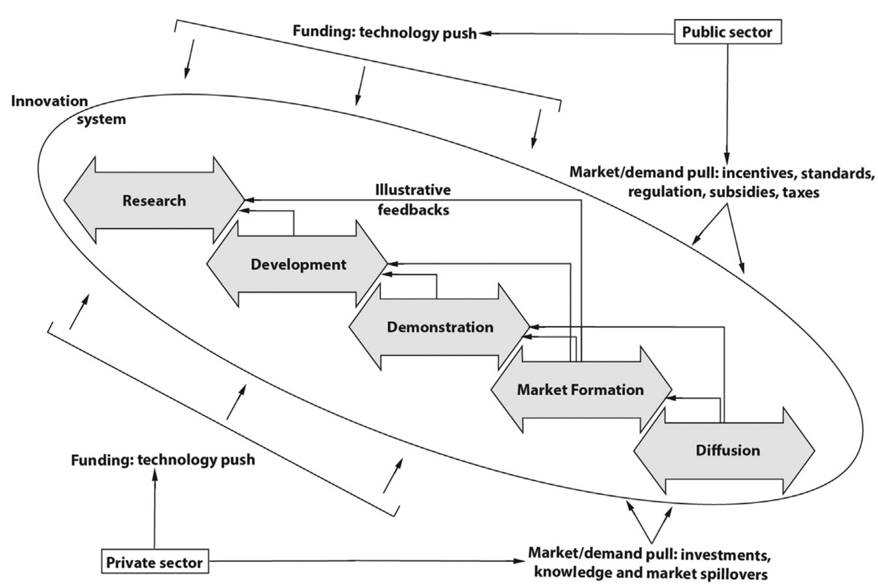

Fig. 2. The role of policies and investments in the innovation system (adapted from [6,30]).

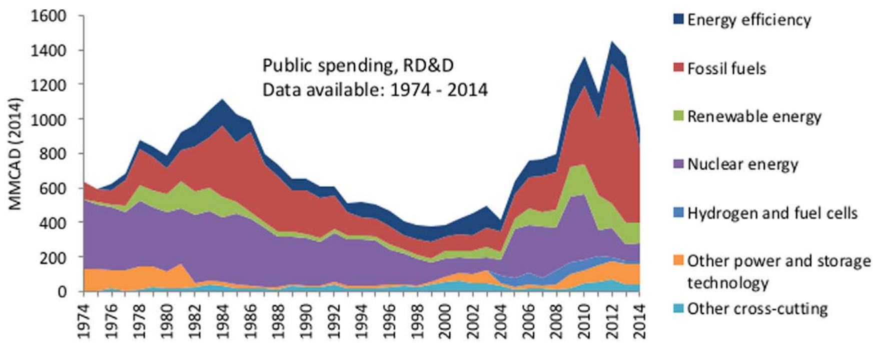

Fig. 3. Public spending in RD & D by energy category.

as from Statistics Canada. Grant Connect provides searchable, detailed information on all Canadian grant-making foundations, hundreds of corporate community investment programs, government funding programs, and United States foundations that will fund Canadian organizations. The search criteria included all funders falling under the category “environment-energy use and climate change.”

Where data were not available, the developers of different financing mechanisms and grant programs were contacted to complete a questionnaire. The information was gathered through interviews (e-mail and/or phone) or by the information gathered through their websites. The following questions were addressed:

1. What types of funding mechanisms are available across Canada to support greenhouse gas reductions and/ or clean energy development and/or use?
2. Who are the beneficiaries of these funding mechanisms?
3. What do these programs support?
4. What is the funding source?
5. What is the amount committed to these funds?

For this study, we focus specifically on what types of programs are supported and the amount of funding committed.

3.2. International, national, and provincial policy review

Improving the performance of Canada's ETIS depends not only on the investments across stages of innovation and the processes employed for learning and technology adoption, but also on technology push and market pull policies [30]. International, federal and provincial/regional policies employed in Canada to support innovation in greenhouse gas reductions have been compiled and reviewed. These policies were organized in terms of their contributions to technology push and market pull dynamics. Technology-push policies stimulate R & D, aimed particularly at decreasing the costs of low carbon technologies that are far from being competitive in existing markets [31]. Measures may include publicly-funded R & D or R & D tax credits. Conversely, demand-pull policies improve the demand for lower-emission technologies specifically by creating a market through standards, increasing private incentives and encouraging learning-by-doing actions [31]. Instruments might include indirect approaches, such as emissions taxes, or more direct approaches, such as renewable portfolio standards (Fig. 2). Policies were then qualitatively assessed in terms of overall advancement of clean energy innovation in each region by comparing against emission reductions by province and territory. Policies implemented in regions that have successfully reduced emissions were identified to inform the development of recommendations that support meeting international commitments in the future.

4. Results and discussion

4.1. Review of current investments

The review of investment in clean energy innovation investment focused on two key components: government spending and industry spending. We compiled available data on different stages and categories of innovation, categorized as research and development (R & D), research, development, and demonstration (RD & D), or research, development, demonstration and deployment (RD3), and capital expenditures (CAPEX) on actual energy projects.

4.1.1. Government investment

Public spending data for energy RD & D were compiled in this review to understand better the investment trends in Canada (Fig. 3). Federal RD & D data for the following seven technology categories were collected [32]: (1) energy efficiency, (2) fossil fuels, (3) renewable energy sources, (4) nuclear, (5) hydrogen and fuel cells, (6) other power and storage technologies, (7) other crosscutting technologies and research. With the exception of the last reporting year (2014) when investments dropped, data indicate that there has been a clear trend of increasing Canadian federal investments towards fossil fuels. The share of investment in fossil fuels increased from 15% to 55% from 1974 to 2013. A large portion of this went to carbon capture and storage (CCS), which grew from 0% to 58% of fossil fuel spending from 2003 to 2013. The spending on fossil fuels dropped by just under 50% in 2014, while that of renewables decreased by less than 10%. RD & D spending on renewable energy has increased by 2.7 times over the past decade, but remains only 12% of total government RD & D spending. Spending on fossil fuels increased near four-fold over the same time period. There has been growth in power and storage spending, however, which may also support the growth of renewables. The spending on energy efficiency has largely remained constant over the same time period. The drop in spending in 2014 leaves a question about the trend moving forward, particularly with the election of a new liberal government.

4.1.2. Private investment

We first review industry investments in early innovation followed by CAPEX in actual projects. The only available data were R & D rather than RD & D, reinforcing that private investment data are limited in the public domain. The dataset [33] covered a shorter timescale than that of government, ranging from 2009 to 2013 (Fig. 4). Results show a trend of increasing investment, but weighted towards fossil fuels. Fossil fuel spending increased from \$0.9 to 1.5 billion (CAD), maintaining just over 70% of the total amount invested over the time period evaluated. The portion spent specifically on CCS was not readily available in this dataset.

The second portion of the industry data review involved compiling a database and analyzing CAPEX on clean energy technology (Fig. 5). Investment data were gathered and evaluated from the Bloomberg terminal as firms rarely release disaggregated investment data

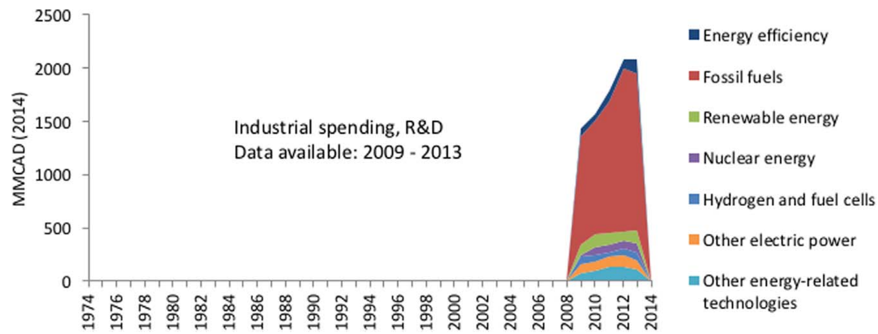

Fig. 4. Amount of R & D funds invested annually by industry [32].

(Fig. 5a). With the exception of the spike in 2008 biofuel capital expenditures, the Bloomberg data indicated there were no major changes in the magnitude of the spending from 2003 to 2014 but rather in the composition of the spending. Prior to 2008, the spending was mostly aimed towards large hydropower, which later transitioned to wind energy. Data from the Bloomberg terminal were found to be incomplete as not all companies reported CAPEX. As a result, Clean Energy Canada data [34] were also included in the analysis (Fig. 5b). The latter dataset used Bloomberg New Energy Finance data that were scaled according to capacity additions to estimate full expenditures. Results indicate a similar trend in capital expenditures for wind energy for both datasets. Similar to the other datasets, spending on fossil fuels

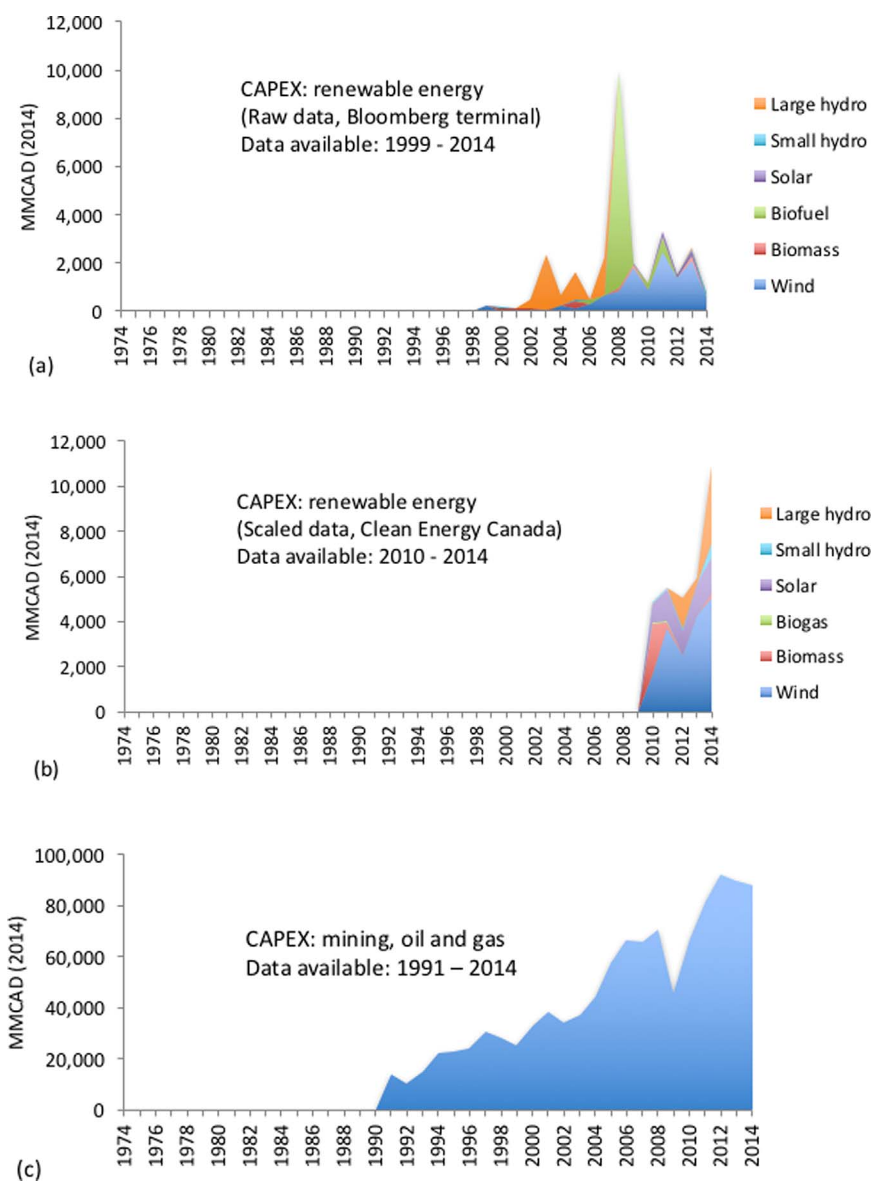

Fig. 5. (a, b, c). CAPEX reported by (a) Bloomberg on renewable energy, (b) Clean Energy Canada on renewable energy, and (c) Statistics Canada on mining, oil, and gas. Bloomberg raw data is presented in (a) while Clean Energy Canada scaled raw data to estimate full CAPEX according to capacity additions. Petroleum and natural gas alone stood at $71.6 billion CAD and $78.5 billion CAD in 2014 and 2015 respectively [33].

Table 1
Funding categories evaluated in the review of financing mechanisms available for clean energy.

Program	Description
Energy conservation	Energy efficiency, smart grid and energy storage technologies.
Capacity building	Training, workshops or mentorship programs to develop clean technologies.
Transportation and agriculture/livestock	Transportation and agriculture developments.
Geo	Renewable energy such as hydro, marine, geothermal and wind.
Bioenergy	Technologies that use biomass as their main source of energy. This includes biofuels, waste to energy, biomass to energy, biogas to energy.
Solar	Technologies that use sunlight as their main source of energy. This includes solar-PV, solar thermal, solar thermal concentrated.
Business development and other	R & D and business growth in science, technology, arts and literature. This category also includes basic and applied research as well as business growth and development.

far outweighed that of renewables (Fig. 5c). Petroleum and natural gas CAPEX were just over 10 times that of renewables [34]. The gap has narrowed in the past two years, with renewables growing from 7.8% of fossil fuel capital expenditures to 9.5%.

4.1.3. Additional financing for clean energy

Financing in Canada is readily available for clean energy, but information describing what is available was not found in a comprehensive database. To address this gap, we compiled available data on the total financing available using archival sources and supplemented it with survey data. The examination of available financing mechanisms for clean energy included 193 funding programs from DEC database and 204 grant programs in the Grant Connect database. The funding was categorized into seven different program categories and reviewed in terms of the amount of funding available. The categories included energy technologies along with capacity building and business development (Table 1). Of the 397 financing alternatives available, funding agencies included: the federal government (67 grants/programs), provincial government (123 grants/programs), municipalities (9 grants/programs), private sector (87 grants/programs), universities (2 grants/programs), and non-governmental organizations (109 grants/programs).

Results indicate that financing mechanisms are readily available across Canada (Fig. 6); however, there is no comprehensive database for investors to use in their decisions. Funding is provided for smaller grants (e.g. $10,000 and less) as well as for programs as large as $500 million and more. Small grants are used to support education, training, and the promotion of less costly innovations while larger grants are used to support technology advancement. Investors may not typically consider funding sources for capacity building; however, such funds may support community development. A more comprehensive database with adequate metadata may lead to the use of funding that encourages community support for energy projects and concurrent development (e.g. infrastructure in remote communities).

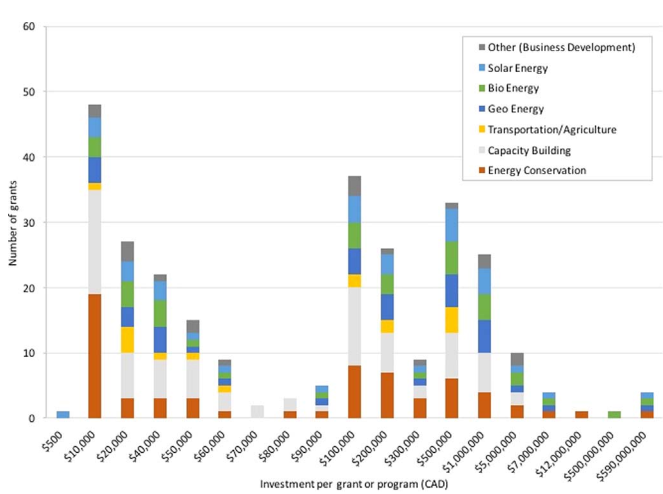

Fig. 6. Amount of money per grant or program. Data were not available in a form where they were disaggregated temporally, indicating a need for a more comprehensive database for investors.

As these data were compiled for the purpose of this analysis, we acknowledge the limitations in this first data collection effort. First, the dataset is still incomplete as the percentage of survey responses was low (24%). Additionally, there were difficulties in categorizing the amount committed per grant, as financing was available in different forms, covering different time periods (e.g. equity tax credit, rebate, loan, wage subsidy, etc.). Future work may include more questions on temporal aspects of the funding deployed, permitting further longitudinal examination of the data. Some categories were too broad to characterize specifically in the context of energy development; for example, programs supported under business development may support a larger scientific scope than just for energy. Additional specificity around the type of financing would support a more comprehensive dataset. If compiled and packaged by province alongside available policies, investors may find attractive options that encourage new developments.

4.2. International, national, and provincial policy review

Canada is a federalist political system, with the Canadian Constitution allocating the governance of resource extraction to the provinces and territories [29]. The achievement of national and international greenhouse gas emissions goals may be challenging if climate policies are not carefully planned and coordinated. Two strategies have been proposed to manage this challenge [35]: (1) create incentives for companies to work with public actors, and (2) enhance collaboration between federal and provincial governments. Such recommendations can be advanced by identifying the most attractive combinations of policies and investments for use in a more cooperative model of federalism. A variety of policy tools are available specifically to promote innovation; for example, direct support of RD3, economic incentives, regulations, standards, and federal procurement [36]. These policies can be more generally characterized in terms of their contributions to technology push and market pull dynamics. It is recognized that innovation policies should be developed considering overall ETIS, with consciousness of the interdependencies across time, space, and actors [6]. As such, policies should not be developed with focus on one particular aspect of the system, but rather coherently with recognition of the system dynamics. We review existing policies in light of the knowledge we have captured regarding the present innovation system in Canada. Policies are organized at varying governance levels (international, federal, and provincial/regional) and are characterized as either technology push or market pull. More specifically, policies are classified as technology push, direct market pull (renewable or clean energy requirements), or indirect market pull (other mechanisms such as taxes, tariffs, and incentives). Policies are thus presented in an organized way such that they can be qualitatively discussed relative to emissions performance across tiers of governance.

Table 2
Cross-provincial and international initiatives that support the development of clean energy innovation (adapted from [37]).

Cross-provincial/international	Canadian participants	International participants	Technology push	Market pull (direct)[a]	Market pull (indirect)[b]
UNFCCC (e.g. Copenhagen accord, Paris agreement): international commitments to greenhouse gas reduction	Federal government	Global participant countries	–	–	Y
The Western Climate Initiative: emissions trading policies	B.C., Manitoba, Ontario, Quebec	California	–	–	Y
International Carbon Action Partnership: working to develop cap and trade programs	B.C., Ontario, Quebec	Regions from the EU, North America, Asia Pacific	–	–	Y
Climate registry: reporting systems	Canadian provinces	United States	–	–	Y
Climate Change Action Plan: voluntary commitments to reduce emissions	New Brunswick, Prince Edward Island, Newfoundland and Labrador	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont	–	–	Y
G20 commitment to reducing fossil fuel subsidies	Federal government	G20 countries	–	–	Y

[a] Direct approaches create markets by requiring a percentage of clean energy or by financial support of clean energy projects: renewable portfolio standards and adoption subsidies.
[b] Indirect approaches contribute to the development of clean energy markets but do not create markets directly, such as emissions taxes, trading, and removing high carbon subsidies.

4.2.1. International initiatives

Through Canada's involvement in international initiatives to reduce emissions and mitigate climate change, the nation has committed to a number of agreements (e.g. Kyoto Protocol). The overall history of meeting targets has not been one of success, exemplified yet again in the expectations for the commitment through the Copenhagen Accord. In addition to this accord, a number of other international initiatives are ongoing (Table 2).

All international commitments reviewed in Table 2 were categorized as indirect market pull and are voluntary or weak in enforcement. Federalist political systems can experience challenges when negotiations happen at the national level if subnational governments are unwilling to commit to achieving the goals outlined in the agreement. For example, the development of natural resources in Canada is managed by provincial powers – if the economic development of a resource is in conflict with international climate goals, a province may not agree to comply with the nation's negotiations. Such international commitments thus require provincial and territorial support in their achievement. While Canada is unlikely to meet commitments made through the Copenhagen Accord, fossil fuel subsidies were indeed reduced in the 2010–2011 window in agreement with the G20 commitment [38]. This may suggest achievement in meeting commitments; however, the reduction is due primarily to the expiry of policies rather than commitments to reduce subsidies (specifically, the expiry of the Energy Industry Drilling Stimulus). Canada does participate in the IEA's Renewable Energy Technology Deployment (RETD) Technology Management Programme [39], though this programme is not specifically a technology push or direct market pull policy. The goal of the RETD is to enhance international cooperation on policies, measures and market instruments that advance the deployment of renewable energy technologies.

4.2.2. Federal initiatives

While the development of natural resources is the constitutional responsibility of the provincial government, the advancement of RD & D in innovation is unrestricted from a governance perspective. The key challenge is that project implementation (deployment and diffusion) depends in large part on provinces and their respective energy strategies. The federal government can support cost reductions through investing in technology innovation; however, the involvement of provincial powers may be encouraged to support investors in realizing profits from clean projects. The majority of national policies were thus found to encompass only a portion of Canada's energy system and do not address large emitters (Table 3). Coal-fired power plant emissions standards were the only exception and have only recently been applied nationally [40]. In the absence of such requirements, emission reductions have yet to be realized. Direct market pull policies have the most influence over energy project investment decisions if coupled with support from federal investments in technology development and deployment. The remainder of the federal policies is aimed at end-uses. Overall, there is no comprehensive strategy from a federal perspective to encourage investments in clean energy other than CCS in recent years, reinforced by the historic weight of federal RD3 on fossil fuels.

There is presently an opportunity for a model of cooperative federalism to support the development of a more comprehensive clean energy plan across provinces and territories through the Canadian Energy Strategy [42]. Through such an approach, the challenges that federalist political systems may pose to achieving climate goals can be addressed; however, the Canadian Energy Strategy is not a binding commitment. The goals of the strategy include the development of complementary carbon management across Canada, the support for efficient deployment of clean and renewable energy across regions and the acceleration of clean energy innovation. The key challenge remains in developing a model to which provinces and territories can commit that adheres to the Canadian Constitution's allocation of power with

Table 3
Federal and regional policy instruments [40,41].

Federal measures	Technology push	Market pull (direct)[a]	Market pull (indirect)[b]
5% Renewable Fuel Content Regulation for Gasoline 2% Renewable Fuel Content Regulation for Diesel fuel and Heating Oil	–	Y	–
Light-Duty Vehicle Greenhouse Gas Emissions Regulations (up to 2025)	–	–	Y
Electricity Performance Standard for Coal Fired Generation	–	–	Y
Strengthened Energy Efficiency Standards	–	–	Y
Eco-Initiatives (Program closed in 2014):	Y	–	–
● ecoENERGY for Renewable Power			
● ecoENERGY Retrofit Initiative			
● ecoENERGY for Buildings and Houses			
● ecoENERGY for Industry			
● ecoFreight Program			
● ecoTechnology for Vehicles Program			
● ecoENERGY for Fleets			
● ecoMobility			
● ecoENERGY for Renewable Heat			
● ecoAUTO Rebate Program			
● ecoENERGY for Personal Vehicles Initiative			
● ecoENERGY for Biofuels Initiative			
● ecoAGRICULTURE Biofuels Capital Initiative			
● ecoENERGY Technology Initiative			
Technology Development and Deployment	Y	–	–
Energy efficiency regulation, codes and standards for buildings and homes	–	–	Y
Incandescent Lighting Phase-Out Program	–	Y	–
Canadian Intellectual Property Office Green Technology Patents Program	Y	–	–
Passenger Automobile And Light Truck Greenhouse Gas Emission Regulations 2017–2025	–	–	Y
– Heavy Duty Vehicle Greenhouse Gas Emission Regulations			
– BLIERs (may indirectly affect greenhouse gases)			
– Marine spark-ignition engine and off-road recreational vehicle emission regulations			
– Regulations Amending Off-road Compression-Ignition Emission Regulations			
– National Action Plan on Ozone-depleting substances (ODS) and their Halocarbon Alternatives			
– - Environmental Code of Practice for Elimination of Fluorocarbon Emissions from Refrigeration and Air Conditioning Systems			

[a] Direct approaches create markets by requiring a percentage of clean energy or by financial support of clean energy projects: renewable portfolio standards and adoption subsidies.
[b] Indirect approaches contribute to the development of clean energy markets but do not create markets directly, such as emissions taxes, trading, and removing high carbon subsidies.

respect to natural resources.

4.2.3. Provincial, territorial, and regional initiatives

Greenhouse gas emissions by province or territory are influenced by the resources that are being developed in the region as well as the technologies being employed in energy and industrial processes. The largest contribution to Canada's total greenhouse gas emissions is from the oil and gas sector at 173 Megatonnes (Mt), followed by transportation (165 Mt), electricity (86 Mt), buildings (80 Mt), emissions-intensive and trade-exposed industries (78 Mt), agriculture (69 Mt) and finally waste and others (47 Mt) (Environment Canada, 2014 [43]). The regulation of these activities is divided between federal and provincial powers.

Among other factors, the presence and absence of climate policies across Canadian provinces and territories reflects the regions' energy reserves as well as the political will of the respective governments to achieve overall greenhouse gas reductions. Top performers for greenhouse gas reductions between 2005 and 2012 are Ontario (19% reduction), Nova Scotia (18% reduction), New Brunswick (18% reduction), as well as the Yukon (20% reduction), Northwest Territories and Nunavut (15% reduction) (Table 4). Ontario reduced emissions by the largest magnitude (40 $MtCO_2e$). Alberta, Saskatchewan, and Manitoba increased their emissions by 8%, 5%, and 1% respectively. Alberta contributed the highest emissions growth in large part due to the development of the oil sands, which has historically proven to be a lucrative development when oil prices are high enough.

We present a review of provincial and territorial policies, categorized as technology push and market pull (direct and/or indirect) (Table 5). Due to the constitutional importance of sub-national governance in the management of natural resources, generating an understanding the nature of provincial and territorial policies relative to emissions performance is critical (even if qualitative). Across Canada, policies were found to be incoherent across provinces/regions, signifying the importance of sub-national cooperation in meeting international commitments.

Table 4
Greenhouse gases by province/territory [43].

Province or territory[a]	1990 $MtCO_2e$	2005 $MtCO_2e$	2012 $MtCO_2e$	Percentage change (2005–2012)
Alberta	170	232	249	8%
Ontario	177	207	167	−19%
Quebec	84	86	78	−9%
Saskatchewan	44	71	75	5%
British Columbia	49	62	60	−4%
Manitoba	19	21	21	< 1%
Nova Scotia	19	23	19	−18%
New Brunswick	16	20	16	−18%
Newfoundland and Labrador	9.2	9.9	8.7	−12%
Prince Edward Island	2	2.2	1.9	−14%
Northwest Territories and Nunavut	1.5	2	1.7	−15%
Yukon	0.5	0.5	0.4	−20%

[a] Provinces and territories are ranked in order of highest to lowest 2012 emissions.

To provide a qualitative assessment of the correlation, policies implemented by province are reviewed in light of provincial emissions performance. Top performers in greenhouse gas reductions from 2005 to 2012 included Ontario (−19%), Nova Scotia (−18%), New Brunswick (−18%), Quebec (−9%), and the Yukon (−20%). The common thread in

Table 5
Provincial and regional climate policy instruments [37,39].

Regional measures	Technology push	Market pull (direct)[a]	Market pull (indirect)[b]
Alberta			
Climate Leadership Plan (proposed policy package)	Y	Y	Y
Specified Gas Emitter's Regulation (SGER)	–	–	Y
Climate Change Emissions Management Corporation	Y	–	–
Alberta's Offset System	–	–	Y
Additional technology R & D (e.g. through Alberta Innovates)	Y	–	–
Net billing[c]	–	–	Y
Landfill gas regulations (BC, ON, AB)	–	–	Y
Alberta Flaring and Venting emission control policy (Alberta ERCB Directive 60)	–	–	Y
British Columbia			
BC Clean Energy Act (policy package)	Y	Y	Y
BC Carbon Tax (update to $30/tonne)	–	–	Y
Standing Offer Program for Renewable Energy[d]	–	–	Y
Energy Efficiency Programs	–	–	–
Low Carbon Fuel Standards (WCI)	–	–	Y
Appliance Efficiency and Building Standards (WCI)	–	–	Y
B.C. emissions offsets regulations	–	–	Y
Methanol, hydrogen fuel tax exemptions	–	Y	–
Landfill gas regulations (BC, ON, AB)	–	–	Y
BC Oil and Gas Commission's Flaring, Incinerating and Venting Reduction Guideline	–	–	Y
Regulations requiring implementation of National Emission Standard CSA B415 (USA EPA standards)	–	–	Y
Manitoba			
Low Carbon Fuel Standards (WCI)	–	–	Y
Request for proposals to develop 1000 MW of wind power over a decade (2005–2006)	–	Y	–
Appliance Efficiency and Building Standards (WCI)	–	–	Y
Penalties for suppliers who do not meet minimum renewable fuel content	–	Y	–
Manufacturing tax credit for renewable energy use	–	Y	–
Venting and flaring requirements in permitting processes (MB, NFLD)	–	–	Y
New Brunswick			
Renewable Portfolio Standard (RPS) (10% by 2016)	–	Y	–
Policy Commitment to Increase RPS (40% by 2020)	–	Y	–
Net Metering for Small Producers	–	–	Y
Nova Scotia			
Renewable portfolio standard (40% by 2020)	–	Y	–
Demand-side management policies for electricity	–	–	Y
Cap on Electricity Sector Greenhouse Gas Emissions	–	–	Y
Community Feed-in Tariff	–	Y	–
Net Metering	–	–	Y
Landfill Management	–	–	Y
Newfoundland and Labrador			
Venting and flaring requirements in permitting processes (MB, NFLD)	–	–	Y
Regulations requiring implementation of National Emission Standard CSA B415	–	–	Y
Northwest territories			
Renewable Energy Fund	Y	–	–
Renewable Energy Strategies	–	–	Y
Nunavut			
Ikummatiit – energy strategy	–	–	Y
Ontario			
Coal-Fired Phase Out	–	Y	–
Policy commitment (10,700 MW of renewable capacity by 2016, excluding hydro)	–	Y	–
Standing Offer Program for Renewable Energy	–	–	Y
Feed-In-Tariff Energy Efficiency Standards and Smaller Projects	–	Y	–
Net metering for Smaller Producers	–	–	Y
Appliance Efficiency, Building Standards/Retrofits	–	–	Y
Energy Efficiency Programs	–	–	Y
Low Carbon Fuel Standards (WCI)	–	–	Y
Appliance Efficiency and Building Standards (WCI)	–	–	Y
Landfill gas regulations (BC, ON, AB)	–	Y	Y
Prince Edward Island			
Policy target of 30% renewable energy by 2013	–	Y	–
Feed-in Tariff for Wind Energy	–	Y	–
Net Metering	–	–	Y
Quebec			
Cap and Trade	–	–	Y
Carbon Levy	–	–	Y
Low Carbon Fuel Standards (WCI)	–	–	Y
Policy commitment (4000 MW of wind by 2015)	–	Y	–
Net metering for Small Producers	–	–	Y
Appliance Efficiency and Building Standards (WCI)	–	–	Y
Renewable fuel tax reimbursement/income tax credit	–	Y	–
Landfill Gas Management	–	–	Y
Regulations requiring implementation of National Emission Standard CSA B415 (USA EPA	–	–	Y

(continued on next page)

Table 5 *(continued)*

Regional measures	Technology push	Market pull (direct)[a]	Market pull (indirect)[b]
standards)			
Quebec new standard for large heaters and boilers	–	–	Y
Saskatchewan			
Policy commitment (double wind capacity to 9% of total generating capacity)	–	Y	–
Net metering for Small Producers	–	–	Y
Renewable fuels distributor tax credit for ethanol produced and consumed in the province	–	Y	–
Saskatchewan Energy and Resources Guide S-10/S-20 *"Gas Conservation Standards, and Upstream Flaring and Incineration Specifications"*	–	–	Y
Yukon			
Policy commitment (20% increase in energy supply by 2020)	–	Y	–

[a] Direct approaches create markets by requiring a percentage of clean energy or by financial support of clean energy projects: renewable portfolio standards and adoption subsidies.
[b] Indirect approaches contribute to the development of clean energy markets but do not create markets directly, such as emissions taxes, trading, and removing high carbon subsidies.
[c] Net metering and net billing enable grid-connected generators that are owned by customers (e.g. house-scale PV) to offset some or all their electricity consumption by receiving payment or credit for excess energy that is sent back to the grid [44].
[d] The Standing Offer Program is a non-competitive, provincial program that permits BC Hydro to purchase electricity from small, clean energy projects for a pre-set price through a stream-lined process that includes a simplified contract [45].

the policies for each of these top performers is the presence of a renewable energy requirement. Ontario reduced emissions by the greatest total amount, where the province's renewable energy requirement was combined with a coal-fired phase-out policy and a feed-in-tariff for renewable energy. Ontario's coal-phase out policy put an end to coal use by 2014 [46]. Coal accounted for 25% of the province's greenhouse gas emissions in 2007 with the phase-out resulting in a reduction of 34 Mt of CO_2 emissions per year. Feed-in-tariffs were common among three provinces that successfully reduced emissions: Ontario, Nova Scotia, and P.E.I. (the latter with a 14% reduction). Overall, direct market pull policies that covered significant portions of the energy system were implemented in provinces with success in reducing emissions.

Only three regions in Canada experienced increases in emissions: Alberta (8%), Saskatchewan (5%) and Manitoba (1%). Alberta has been a leader in terms of legislating a climate policy in 2007 (the Specified Gas Emitters Regulation or SGER); however, emissions were regulated on an intensity basis, so an overall reduction in provincial emissions has not yet been realized. Though a provincial reduction in emissions was not achieved, it must be noted that the oil sands sector has significantly reduced the overall emissions intensity. Using public information, Englander et al. [47] found that life cycle oil sands emissions have declined (on average) from165 gCO_2e/MJ higher heating value (HHV) of reformulated gasoline (RFG) to 105 gCO_2e/MJ HHV RFG. The carbon intensity of oil sands production (on a pathway-average basis) still ranges from 12% to 24% higher than those values for conventional oil production. While there is a commitment for investing in the development of clean technology through the SGER, previous Albertan policies have not included phasing out higher emissions energy sources (e.g. coal) or renewable requirements. The proposed Climate Leadership Plan does include a partial coal phase-out, where coal will be replaced with low-carbon electricity sources or no-pollution technology will be employed, a cap on oil sands emissions, and a renewable requirement of 30% of generation [48]. Saskatchewan included a commitment to double wind capacity from 2006 to 2020; however, it is too early to see the benefits from this target. Additionally, to achieve emission reductions, the new capacity would have to replace higher emissions sources (unless reductions were achieved concurrently in other sectors). While Manitoba expressed an interest in the installation of 1000 MW of wind capacity by 2016, only 238 MW has been reported as installed so far [49]. The challenge in meeting actual reductions for low performers may be driven by the lack of compliance and commitment to reducing net emissions from existing fossil sources, noted by the combination of poor performance and lack of direct market pull policies. In addition, policy effectiveness has been found to require autonomy from politicians and rigidity in the policy-making process [50]. If policies developed from Alberta's Climate Leadership Plan (which does include several policies that were in place in high performing regions, such as coal phase-out) reflect the same commitment as the province's legislated SGER, then the province may be successful in reducing emissions. Finally, individual projects can make a significant contribution to renewable capacity additions in a small economy (e.g. the Muskrat Falls hydropower project in Newfoundland and Labrador) or for the advancement of overall innovation (e.g. CCS implemented in Shell Canada's Quest project).

New policies continue to evolve internationally, nationally and in different regions of the country. Policy reviews, such as the one presented here, should be continually updated to stay abreast new developments. For example, the recently proposed Climate Leadership Plan in Alberta may prove to change the landscape for the future of emissions in the province. Conversely, Saskatchewan, Manitoba, and the northern territories did not add any renewable power capacity in 2014 or any new climate and clean energy policies [42]. International climate agreements are frequently updated along with national commitments to such policies: the coordination of national and sub-national policies is critical to the achievement of such goals. Finally, the election and re-election of federal governments shapes national strategy.

5. Discussion and policy implications

Energy technology innovation is increasingly recognized as a key driver to reducing greenhouse gas emissions globally. We present a systematic review that can be employed to evaluate and improve the role of innovation in meeting international greenhouse gas emissions targets using Canada as a case study. Our review examines existing public and private funding, available financing mechanisms, and climate policies relative to greenhouse gas emissions performance. Canadian emissions targets are consistently not realized; however, this trend can be reversed with careful design of investment and policies provided there are supportive political decisions. While Canada has a large hydrocarbon resource, notably Alberta's oil sands, the nation is also a global leader in renewable and clean energy. The key political challenge is balancing economic gains from the energy sector with greenhouse gas reductions. With increasing competitiveness of renewable and clean energy, there is growing opportunity to leverage clean energy innovation as a step towards a low carbon future. Our review of Canada's energy technology innovation system enabled the identification of data requirements, research needs, and policy gaps. Results point to the importance of the roles of both government and industry in advancing clean energy, through investment decisions but also in the development of clean energy policies.

Investments in carbon intensive energy far outweigh those in cleaner energy in Canada, noted by high investments in fossil fuels by both government and industry. Public investments in RD & D were assessed along with industrial R & D and CAPEX. Investments were significantly weighted towards fossil fuels for all categories. Capital expenditures in oil and gas typically outweigh those in renewables by over 10 times. The gap has narrowed in the past two years, with renewables growing from 7.8% of fossil fuel capital expenditures to 9.5%. While valuable to compile the data, it must be noted that research, development, and deployment investments by governments and industry were not categorized consistently (RD & D for the former and R & D for the latter). Moreover, the categories of energy technologies were inconsistently reported across sources. Financing mechanisms are readily available; however, they are not publically accessible in a comprehensive database for investors. Investors may be more attracted to invest in Canadian clean energy if they had access to the full suite of existing incentives; more specifically, the types of policy packages and financing mechanisms that are available by region and energy type. Additionally, data should indicate the timescale of the funding grant and/or program such that project managers and investors can plan to spend efficiently in the event of a successful application.

Providing access to data, knowledge and insights that assist in making sound investments should reduce information gaps and asymmetries between both government and industry. Such transparency can inform government's role in reducing the innovation gap and support private investors in making more strategic investments. There is no publically available, complete, and disaggregated private investment dataset (consistent with published literature) – such data should be reported in alignment with available public spending. More specifically, the energy technologies and system boundaries (R & D versus RD & D) associated with historic datasets should be consistent and made transparent over similar time horizons (rather than partial datasets). How financing is deployed in light of potential funding gaps should be better understood. Funders can then select how their investments may yield the highest results in light of available financing and their policy preferences. With a full picture of investment data and financing mechanisms, an evaluation can be made to determine if investments are weighted towards one particular aspect of the system, rendering the innovation process more or less efficient. If the emphasis is placed on basic research, output from this phase of innovation may be inflated when compared to what the private sector is willing to fund in later stages of the innovation sequence. If government funding is concentrated solely on early R & D, less attention may be placed on supporting intermediate-stage activities or coordinating research projects across the innovation process. Access to data and information can support coordinated efforts to bridge the innovation gap, particularly for the case of technologies with high potential for emissions and cost reductions. Present results reinforce the need for improved access to information on incentives and funding; however, the data are still too aggregate and inconsistent to detail the necessary steps to improve overall system efficiency.

Success in achieving reductions in greenhouse gas emissions was inconsistent across provinces and appears to be influenced by the strength of the policies in place. Three policies applied by top performers included renewable energy requirements, coal-fired phase-out, and feed-in-tariffs. Only three regions in Canada experienced increases in emissions over the timescale noted: Alberta, Saskatchewan, and Manitoba. These provinces either did not have or meet direct market pull policies that were in effect over the time period. In the future, policies should also be assessed relative to a region's available financing mechanisms to help determine the right balance of overall system efficiency. The new federal electricity emissions standards will support transitions from the present coal generation fleet to lower carbon sources in the electric sector; however, the standards are too early in their implementation to determine the success of the policy. Policies were found to be fragmented and incoherent across horizontal and vertical levels of governance. Significant opportunity exists to advance cooperative federalism through mechanisms such as the implementation of the Canadian Energy Strategy. The goals outlined in the strategy do not include hard targets or commitments at this point; however, such goals may be achieved depending on the evolution of the strategy.

While clean energy technologies and policies can be effective at reducing emissions, there may be additional economic costs borne to society during the transition. Who should pay for the environmental costs of energy and the transition to a lower carbon future? In the case of Ontario's successful greenhouse gas emissions reductions, the province and consumer bore the costs of the policies [46,51]; while at the project-level, Shell Canada's Quest project was initiated with $745 million over 15 years of funding from the Alberta government [52]. Such cases warrant thoughtful evaluation to inform recommendations for policy improvements and cost reductions in future developments.

Both policy commitment and investments are required to advance innovation and realize emission reductions. To effectively meet international targets, Canada will have to identify what policies and investments are required in addition to the feasibility of such changes. Overall, investments and policies have not been aligned with international emissions reduction targets. Capital investments are required to deploy the clean technologies required to realize emission reductions targets and policies must be developed to encourage these investments. The most success has been achieved in regions where phasing out high carbon fuel sources is coupled with requirements for clean capacity additions. Overall, policies remain fragmented across Canada. The Canadian Energy Strategy may provide a new avenue for cooperative federalism in Canada, one that permits provinces to collectively overcome the governance challenges in federalist political systems faced in meeting international greenhouse gas commitments. Canada has two paths to commencing a successful track in meeting greenhouse gas emissions commitments. On the one hand, the country can make a commitment and build a path to meeting the target through contributing to clean energy innovation, encouraging investments in low carbon projects, and implementing policies that cover high emitting sectors of the economy. On the other hand, Canada may choose to commit to achievable targets by evaluating the feasibility of both investment increases and implementation of policies required to incent such increases, alongside an evaluation of the amount of time required to realize emission reductions.

Through characterizing a country's energy technology innovation system, targeted policy recommendations can be developed to improve the ability of the nation to meet international commitments. Multiple questions remain regarding the efficiency of the present system that can be addressed in future work. Are viable technologies being encouraged or advanced along innovation stages? Is funding being aimed at the most cost-effective programs when examining innovation from a systems perspective? Are financing mechanisms well aligned with policies? Answering such questions will encourage more attractive packaging of incentives for clean energy investors.

A systems perspective encourages coordination between financing and policy, providing additional support achieving emissions reductions goals. Our model for a systematic review can be applied broadly across governance levels and regions to gain a more in-depth understanding of improvements that can be made to energy technology innovation systems, particularly in federalist political systems with large fossil fuel reserves. By creating a greater understanding of the role of innovation in greenhouse gas emissions reductions, recommendations can be made for improving financing, data transparency, and policy effectiveness, thereby facilitating the transition to a lower-carbon and more sustainable energy future.

Funding

Funding for this project included a start-up Grant from Simon Fraser University (PRSG-N877520), the University of Calgary Start-Up grant: RSO# 1027323 and MITACs internships for several researchers who conducted research at Decentralized Energy Canada (DEC). MITACS connects academic researchers with businesses through co-sponsoring internships. Funding from CMA Alberta (70-14101-RT755823) also supported this project.

Acknowledgements

We would like to acknowledge our research assistants, who provided additional data collection support: Amy Glassman, Jack Middleton, Shivani Sachdev, and Siamak Khorrami. We also received helpful feedback from participants in our webinar.

References

[1] Intergovernmental Panel on Climate Change (IPCC), 2014. Summary for policy-makers. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change; 2014.
[2] Anadon LD, Bunn M Chan G Chan M, Jones C, Kempener R, Lee A, Logar N, Narayanamurti V. Transforming U.S. Energy Innovation, a report of the findings of the Energy Technology Innovation Policy (ETIP) research group, Belfer center for science and international affairs, Harvard Kennedy School, November 2011; 2011.
[3] Gallagher KS, Holdren JP, Sagar AD. Energy technology innovation. Annu Rev Environ Resour 2006;31:193–237. http://dx.doi.org/10.1146/annurev.energy.30.050504.144321.
[4] Margolis R, Kammen DM. Underinvestment: the energy technology and R & D policy challenge. Science 1999;285:690–2. http://dx.doi.org/10.1126/science.285.5428.690.
[5] Nemet GF, Kammen DM. U.S. energy research and development: declining investment, increasing need, and the feasibility of expansion. Energy Policy 2007;35(1):746–55. http://dx.doi.org/10.1016/j.enpol.2005.12.012.
[6] Gallagher KS, Grubler A, Kuhl L, Nemet G, Wilson C. The energy technology innovation system. Annu Rev Environ Resour 2012;37:137–62. http://dx.doi.org/10.1146/annurev-environ-060311-133915.
[7] Grubler A, Anadón LD, Gallagher KS, Kempener R, O'Rourke A, Wilson C. 21 Global R & D, market formation, and diffusion investments in energy technology innovation. Energy Technol Innov: Learn Hist Success Fail 2013;292.
[8] Office of the Auditor General. Spring report of the commissioner of the environment and sustainable development. Chapter 2 – meeting Canada's 2020 climate change commitments; 2012. ⟨http://www.oag-bvg.gc.ca/internet/English/parl_cesd_201205_02_e_36774.html⟩ [Accessed 16 April 2002].
[9] Environment Canada. Progress toward Canada's greenhouse gas emissions reduction target, environmental indicators; 2015. ⟨https://www.ec.gc.ca/indicateurs-indicators/default.asp?Lang=en & n=CCED3397-1⟩ [Accessed 16 April 2002].
[10] United Nations Framework Convention on Climate Change (UNFCCC). Canada's intended nationally determined contributions; 2016. ⟨http://www4.unfccc.int/submissions/INDC/Published%20Documents/Canada/1/INDC%20-%20Canada%20-%20English.pdf⟩ [Accessed 16 April 2002].
[11] Government of Canada, 2011. State of the nation 2010 — Canada's science, technology and innovation system: imagination to innovation — building Canadian paths to prosperity. Science, technology and innovation council; 2011.
[12] Henderson RM, Newell RG. Introduction and summary. In: Henderson RM, Newell RG, editors. Accelerating energy innovation: insights from multiple sectors. Chicago: University of Chicago Press; 2011. p. 1–24.
[13] Newell RG. The role of markets and policies in delivering innovation for climate change mitigation. Oxf Rev Econ Policy 2010;26(2):253–69. http://dx.doi.org/10.1093/oxrep/grq009.
[14] Anna Bergek, Berggren Christian, KITE Research Group . The impact of environmental policy instruments on innovation: a review of energy and automotive industry studies. Ecol Econ 2014;106:112–23.
[15] Abdmouleh Z, Alammari RA, Gastli A. Review of policies encouraging renewable energy integration and best practices. Renew Sustain Energy Rev 2015;45:249–62.
[16] Romano AA, Scandurra G, Carfora A, Fodor M. Renewable investments: the impact of green policies in developing and developed countries. Renew Sustain Energy Rev 2017;68:738–47.
[17] MacGillivray Andrew, Jeffrey Henry, Wallace Robin. The importance of iteration and deployment in technology development: a study of the impact on wave and tidal stream energy research, development and innovation. Energy Policy 2015;87:542–52.
[18] Kim K, Kim Y. Role of policy in innovation and international trade of renewable energy technology: empirical study of solar PV and wind power technology. Renew Sustain Energy Rev 2015;44:717–27.
[19] Surana K, Anadon LD. Public policy and financial resource mobilization for wind energy in developing countries: a comparison of approaches and outcomes in China and India. Glob Environ Change 2015;35:340–59.
[20] Darmani A, Arvidsson N, Hidalgo A, Albors J. What drives the development of renewable energy technologies? Toward a typology for the systemic drivers. Renew Sustain Energy Rev 2014;38:834–47.
[21] Karltorp K, Guo S, Sandén BA. Handling financial resource mobilisation in technological innovation systems – the case of Chinese wind power. J Clean Prod 2017;142:3872–82.
[22] Sagar AD, Holdren JP. Assessing the global energy innovation system: some key issues. Energy Policy 2002;30(6):465–9. http://dx.doi.org/10.1016/S0301-4215(01)00117-3.
[23] The Breakthrough Institute. Bridging the clean energy valleys of death: helping American energy entrepreneurs meet the nation's energy imperative; 2011. ⟨http://thebreakthrough.org/blog/Valleys_of_Death.pdf⟩ [Accessed 16 April 2002].
[24] Sustainable Development Technology Canada (SDTC). SDTC fills the funding gap; 2015. ⟨https://www.sdtc.ca/en/about-sdtc/sdtc-fills-funding-gap⟩ [Accessed 15 September 2001].
[25] Reichman J, Rai AK, Newell RG, Wiener JB. Intellectual property and alternatives: strategies for green innovation. london, energy, environment and development programme paper. UK: Chatham House; 2008.
[26] Weyent JP. Accelerating the development and diffusion of new energy technologies: beyond the "valley of death". Energy Econ 2011;33(4):674–82. http://dx.doi.org/10.1016/j.eneco.2010.08.008.
[27] Beard RT, Ford GS, Koutsy TM, Spiwak LJ. A valley of death in the innovation sequence: an economic investigation. Res Eval 2009;18(5):343–56. http://dx.doi.org/10.3152/095820209X481057.
[28] Murphy LM, Edwards PL. Bridging the valley of death: transitioning from public to private sector financing. National Renewable Energy Laboratory; 2013, ⟨http://www.globalwateradvisors.com/wp-content/uploads/NREL-Bridging_the_Valley_of_Death1.pdf⟩, [Accessed 16 April 2002].
[29] Wilson C, Grubler A, Sims Gallagher K, Nemet GF. Marginalization of end-use technologies in energy innovation for climate protection. Nat Clim Change 2012;2:780–8. http://dx.doi.org/10.1038/nclimate1576.
[30] IPCC 2007. IPCC fourth assessment report: climate change 2007. Section 2.7.2.3 on the public-sector role in technological change; 2007. ⟨https://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch2s2-7-2-3.html⟩ [Accessed 16 April 2002].
[31] International Energy Agency (IEA). Energy RD & D online data service; 2015. ⟨http://www.iea.org/statistics/RDDonlinedataservice/⟩ [Accessed 16 April 2002].
[32] StatsCan. Industrial energy research and development expenditures and extra-mural payments outside Canada, by area of technology. CANSIM, Table 358-0214; 2015a. ⟨http://www5.statcan.gc.ca/cansim/a26?Lang=eng & retrLang=eng & id=3580214 & & pattern= & stByVal=1 & p1=1 & p2=31 & tabMode=dataTable & csid=⟩ [Accessed 16 April 2002].
[33] StatsCan. Capital expenditures by sector, by province and territory (Canada); 2015b. ⟨http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/busi03a-eng.htm⟩ [Accessed 16 April 2002].
[34] Clean Energy Canada. Tracking the clean energy revolution Canada 2015, methodology report; 2015. ⟨http://cleanenergycanada.org/trackingtherevolution-canada/2015/assets/pdf/MethodologyReport_TERCanada.pdf⟩ [Accessed 16 April 2002].
[35] Fertel C, Bahn O, Vaillancourt K, Waaub P. Canadian energy and climate policies: a SWOT analysis in search of federal/provincial coherence. Energy Policy 2013;63:1139–50. http://dx.doi.org/10.1016/j.enpol.2013.09.057.
[36] Moniz E. Stimulating energy technology innovation. Daedalus 2012;141(2):81–93. http://dx.doi.org/10.1162/DAED_a_00148.
[37] Environment Canada. Canada's emissions trends; 2012. ⟨http://www.ec.gc.ca/Publications/253AE6E6-5E73-4AFC-81B7-9CF440D5D2C5/793-Canada's-Emissions-Trends-2012_e_01.pdf⟩ (Accessed 16 April 2002).
[38] OECD. Canada: inventory of estimated budgetary support and tax expenditures for fossil-fuels. In: Inventory of estimated budgetary support and tax expenditures for fossil fuels. OECD Publishing; 2013, pp. 83–117.
[39] Natural Resources Canada (NRCan), 2013. Canada – a global leader in renewable energy enhancing collaboration on renewable energy technologies. Energy and mines ministers' conference, Yellowknife, Northwest Territories; August 2013. ⟨https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/www/pdf/publications/emmc/renewable_energy_e.pdf⟩ [Accessed 16 April 2002].
[40] Environment Canada. Reduction of carbon dioxide emissions from coal-fired generation of electricity regulations (SOR/2012-167); 2015. ⟨http://www.ec.gc.ca/lcpe-cepa/eng/regulations/detailReg.cfm?IntReg=209⟩ [Accessed 16 April 2002].
[41] Canadian Intellectual Property Office (CIPO). Green technology patents; 2014. ⟨http://brevets-patents.ic.gc.ca/opic-cipo/cpd/eng/help/content/help_green_technologies.html⟩ [Accessed 16 April 2002].
[42] Canadian Energy Strategy. Canadian energy strategy. the council of the federation, Canada's premiers; 2015. ⟨http://www.canadaspremiers.ca/phocadownload/publications/canadian_energy_strategy_eng_fnl.pdf⟩ [Accessed 16 April 2002].
[43] Environment Canada. Greenhouse gas emissions by province and territory – 2012 data; 2014. ⟨https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en & n=18F3BB9C-1⟩ [Accessed 16.04.02].
[44] Government of Alberta. What is micro-generation?; 2016. ⟨http://www.energy.alberta.ca/electricity/microgen.asp⟩ [Accessed 16 April 2002].
[45] B.C. Hydro, 2014. Standing offer program review: engagement guide; April 2014. ⟨https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/independent-power-producers-calls-for-power/standing-offer/standing-offer-program-engagement-guide-april-2014.pdf⟩ [Accessed 16 April 2002].

[46] Harris M, Beck M., Gerasimchuk I. The end of coal: Ontario's coal phase-out. International institute for sustainable development; 2015. ⟨http://www.iisd.org/sites/default/files/publications/end-of-coal-ontario-coal-phase-out.pdf⟩ [Accessed 16 April 2002].
[47] Englander JG, Bharadwaj S, Brandt AR. Historical trends in greenhouse gas emissions of the Alberta oil sands (1970–2010). Environ Res Lett 2013;8(4). http://dx.doi.org/10.1088/1748-9326/8/4/044036.
[48] Government of Alberta. Ending coal pollution, alberta climate leadership plan; 2015. ⟨http://www.alberta.ca/climate-coal-electricity.cfm⟩ [Accessed 16 April 2002].
[49] Energy Manitoba. Manitoba wind projects; 2016. ⟨http://www.energymanitoba.org/renewable_wind_mb.htm⟩ [Accessed 16 April 2002].
[50] Holburn GLF. Assessing and managing regulatory risk in renewable energy: contrasts between Canada and the United States. Energy Policy 2012;45:654–65. http://dx.doi.org/10.1016/j.enpol.2012.03.017.
[51] McKitrick RR. Environmental and economic consequences of Ontario's green energy act. Toronto, Canada: Ontario Prosperity Initiative, Fraser Institute; 2013.
[52] Government of Alberta. Carbon capture and storage projects in Alberta; 2016. ⟨http://www.energy.alberta.ca/CCS/3822.asp⟩ [Accessed 16 April 2002].