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CLIMATE CHANGE SOLUTIONS – SENSIBLE OR MISGUIDED?

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SUMMARY

The landmark Paris Agreement to address climate change officially entered into force in November 2016 and has now been ratified by 185 of 197 parties to the convention. The agreement sets a course for all countries to limit global temperature rise to below 2°C and preferably to below 1.5°C. The latest report of the Intergovernmental Panel on Climate Change (IPCC) warns that global warming is becoming irreversible and that the societal impacts of climate change are calamitous. The IPCC report also carries a positive message that it is still possible to limit global warming to a 1.5°C increase and describes various mitigation pathways that countries could use to reduce their emissions.

But are these mitigation pathways well-founded and coherent? Do they have a possibility of achieving the desired net zero emissions by 2050? Are countries developing the right strategies and taking immediate action to address the decarbonization of their energy systems? What are the policy-relevant indicators on how fast and by how much emissions can be reduced? Are there monumental changes in the energy system driven by technology, competitiveness and social innovation that will fundamentally impact climate policy?

To address the above questions, this study will review the history of climate change agreements and will examine the IPCC's illustrative strategies to limit the temperature increase to 1.5°C. Discussion will also centre on emerging technologies for displacing fossil fuels, including nuclear energy, renewable energy (non-biomass), bioenergy, natural gas as a bridge fuel, carbon capture utilization and storage, and CO_2 retention and negative emissions. It will be shown that despite enthusiastic support for climate mitigation, there are many serious policy and engineering obstacles to greenhouse gas reductions by mid-century.

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We argue that emissions from bioenergy should be treated in the same way as emissions from fossil fuels and this leaves many developed countries in a deep hole for reducing emissions. Based on the analysis in this study, we recommend that Canada pursue strategic policy directions and the design of unique and rational innovation programs.

1.0 INTRODUCTION

Governments around the world are under considerable pressure from their citizens to undertake urgent and bolder actions to get the world on the right track to achieve the Paris Agreement's climate change goals and reduce the risks of global warming. These governments are making multibillion-dollar bets to fund technology and adopt regulations that have broad implications for industrial strategy and development. Industries – from the processing of raw materials to the manufacturing of goods – are also making multibillion-dollar choices on how best to position themselves in a low-carbon economy. It is therefore critical that the decisions being made are effective at the scale required and that the selected technological options have as great a chance as possible to reduce global warming's impact. It is equally important that there be no mismatch between the emissions accounting system and the greenhouse gas (GHG) emissions that actually end up in the atmosphere, based on the best science available. A timely analysis to provide a better understanding of the technological solutions that can be deployed to reduce dependence on GHG-emitting fuels is critical to ensuring that policy and technological decisions are as effective as possible in reducing atmospheric GHG emissions.

2.0 INTERNATIONAL EFFORTS TO DEAL WITH CLIMATE CHANGE

2.1 THE IPCC

The Intergovernmental Panel on Climate Change (IPCC) came into existence in 1988 with the objective of providing policy-makers with scientific assessments on climate change, the risks of human-induced climate change, and to propose options for mitigation and adaptation. Since 1990, the IPCC has produced a series of regular assessment reports. The fifth report was published in 2014 and the sixth report will be finalized in 2022.

2.2 THE UNFCCC

At the Rio Earth Summit in 1992, countries[1] adopted the United Nations Framework Convention on Climate Change (UNFCCC) and the agreement came into force two years later with 195 countries signing on. The countries meet annually at the Conference of the Parties (COP) to negotiate multilateral responses to limit global temperature increases and climate change, and to cope with their impacts. In effect, the UNFCCC handles two related agreements – the Kyoto Protocol and the Paris Agreement.

2.3 KYOTO PROTOCOL

In 1997 under the Kyoto Protocol, the UNFCCC signatories introduced legally binding emission reduction targets for developed countries only. The first commitment period to reach the targets ended in 2013. A second commitment period was agreed to in the Doha Amendment, in which countries were to set binding targets to 2020. The United States never signed on to the Kyoto Protocol and Canada pulled out before the end of the first

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1 For simplicity, the term "countries" is used in lieu of the more general term "parties" used by the UNFCCC.

commitment period. Russia, Japan and New Zealand are not taking part in the second commitment period. The protocol now applies to only around 14 per cent of the world's emissions (Council of the European Union 2018).

2.4 PARIS AGREEMENT AND SUCCEEDING COP MEETING

In December 2015, countries reached a new global agreement on climate change, known as the Paris Agreement. The Paris Agreement entered into force in November 2016 after the conditions for ratification by at least 55 countries, accounting for at least 55 per cent of global greenhouse gas emissions, were met. Currently, of 197 countries of the UNFCCC, 185 countries have ratified the Paris Agreement (United Nations 2019). The essential elements of the Paris Agreement (United Nations 2015) include:

1. Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and aiming to limit the temperature increase to 1.5°C to significantly reduce the risks and impacts of climate change;
2. Reaching global peaking of GHG emissions as soon as possible and undertaking rapid reductions thereafter in accordance with the best available science;
3. Increasing the capacity to adapt to the existing impacts of climate change; and
4. Mobilizing funds from developed countries to support climate mitigation and adaptation in developing countries.

Before and during the Paris conference, countries submitted comprehensive national climate action plans (INDCs) that if successfully implemented, will cause projected temperatures to rise 3.2^{o}C by 2100 (United Nations 2018), far beyond the desired 1.5^{o}C limit.

At COP21 in Paris, Canada committed to a 30-per-cent reduction in GHG emissions by 2030, relative to emissions in 2005. At COP 22 in Marrakech in 2016, Canada further committed to a 70- to 90-per-cent emissions reduction by 2050, relative to 2005.

COP 24, the latest meeting, was held in Katowice, Poland where the countries welcomed "the timely completion of the Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5°C" (see below) and put forward the rulebook to implement the Paris Agreement.

3.0 THE IPCC SPECIAL REPORT ON MEETING 1.5^{O}C

At COP 21 in Paris, the UNFCCC invited the IPCC to provide a special report on the impacts of global warming of 1.5°C above pre-industrial levels and provide global GHG mitigation pathways for limiting the increase to 1.5°C. The IPCC Special Report (2018b) was submitted in October 2018 along with the summary report for policy-makers (IPCC 2018a), ahead of COP 24 in Katowice.

The report provided the evidence that GHG emissions are harming the biosphere and human life in alarming ways that may soon become irreversible. Average global temperatures have already risen by about 1^{o}C above pre-industrial levels. They are on pace to increase to 1.5^{o}C as early as 2030 and 2^{o}C by 2050 and will continue to climb after that. The consequences are potentially disastrous, including record-breaking sea-level rise, flooding, wildfires, extreme weather events, famines and wildlife habitat destruction. Warming is not uniform, and some regions are warming at a faster rate than others; for example, Canada is warming at twice the rate of the rest of the world and Northern Canada is warming at nearly three times the average global rate (Government of Canada 2019).

The economic impacts of climate change for individual countries could be dire. Models of economic loss due to climate change estimate that unmitigated warming is expected to reduce average global incomes roughly 23 per cent by 2100 while widening global income inequality (Burke et al. 2015). The Fourth National Climate Assessment Report (U.S. Global Change Research Program 2018) included a 10 per cent economic contraction for the United States by 2100 and decreased agricultural production. Other countries that will incur large social costs of carbon[2] include India, China and Saudi Arabia (Ricke et al. 2018).

The clear and consistent message from climate scientists is that the body of evidence supporting anthropogenic global warming is very strong and long-term temperature increases provide substantiation of a warming planet (NASA 2019). Moreover, there is compelling evidence that changes in the Earth's climate have already happened, including increasing frequency of weather extremes causing heat waves, droughts, floods, fires and storms. These climate hazards are affecting food security, human health, water supply, infrastructure and natural ecosystems. Without immediate action to limit temperature increases, the impact of global warming could be destructive for humanity.

The IPCC report points to a significant difference between stabilizing the average global temperature at 1.5^{o}C compared to 2^{o}C in terms of substantially higher risks and irreversibility, such as the loss of coral reefs and ecosystems, and the potential for the uncontrolled release of methane hydrates.[3]

4.0 IPCC SCENARIO MODELLING TO LIMIT THE INCREASE TO 1.5^{o}C

Scenarios from climate models can provide insights into relevant policies; for example, on how fast countries must decarbonize and when the peak of global emissions is reached. Included in these assessments are the need for behavioural change, indicated by a decrease in global energy consumption, and the rate of transitioning to both available and immature low-carbon technologies. The recent IPCC summary report for policy-makers (2018a, 14) provided scenarios for constraining global warming to 1.5^{o}C. Table 1 summarizes

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2 The social cost of carbon (SCC) is a commonly employed metric of the expected economic damages from carbon dioxide (CO_2) emissions.

3 Methane hydrates are the world's largest natural gas resource, currently trapped beneath permafrost and ocean sediments. They could have a devastating impact on the climate and cause temperatures to rise far above what has been predicted, given that the comparative impact of methane on climate change is more than 20 times greater than carbon dioxide over a 100-year period.

the four scenarios showing the expansion of low-carbon energy sources in displacing fossil fuel combustion, that are required to limit the increase to 1.5ºC by 2050, based on a range from lower energy to higher energy demand.[4] The overall target is for global emissions to be net zero by 2050. This is consistent with the latest modelling study which shows the need to phase out the use of fossil fuels almost immediately (Smith et al. 2019).

TABLE 1 FOUR ILLUSTRATIVE MITIGATION STRATEGIES AND THEIR PATHWAYS TO LIMIT GLOBAL WARMING TO 1.5ºC.[5]

Required outcomes in 2050 to hold increase to 1.5ºC	Scenario P1	Scenario P2	Scenario P3	Scenario P4
Final Energy Demand (rel. to 2010)	-32%	-5%	21%	44%
CO_2 emissions change (rel. to 2010)	-93%	-95%	-91%	-97%
Primary energy from coal (rel. to 2010)	-97%	- 77%	-73%	-97%
from oil (rel. to 2010)	-87%	- 50%	-81%	-32%
from gas (rel. to 2010)	-74%	- 53%	21%	37%
from nuclear (rel. to 2010)	150%	98%	501%	468%
from renewables – Non biomass (rel. to 2010)	832%	1327%	878%	1137%
from biomass (rel. to 2010)	-11%	49%	121%	418%
Renewable share in electricity	77%	81%	63%	70%
Cumulative CCS until 2100 ($GtCO_2$) of which BECCS ($GtCO_2$)	0 0	348 151	414 283	1191 724
Agricultural CH_4 + N_2O combined emissions (% rel to 2010)	- 27	- 95	-23	41

Source: IPCC (2018a, 14). Reproduced from the report to show achievement of the net emissions reduction by 2050.

According to these results, CO_2 emissions must decrease by over 90 per cent in 2050 in all scenarios (the decrease ranges from 91 per cent to 97 per cent). The faster the decrease happens (e.g., scenario P1) the less the need to resort to the use of immature and controversial carbon removal technologies such as bioenergy with carbon capture and storage, and direct air capture of CO_2. However, a 32-per-cent decrease in energy

4 The referenced report also includes strategies and pathways from now to 2030, in between those of 2050. For simplicity, these strategies have not been included; nor are the insights from the 2050 modelling more relevant.

5 The pathways displacing fossil fuels are based on assumption of energy demand ranging from lower to higher than the demand in 2010 and the concomitant GHG reductions required to hold the increase to 1.5ºC. For simplicity, land area for needed bioenergy crops is not shown.

demand by 2050 relative to 2010 (scenario P1) still requires a 150-per-cent increase in nuclear energy and a more than 800-per-cent increase in non-biomass renewables such as solar, wind and hydro by 2050. This decrease in energy demand and the 93-per-cent GHG emission reduction by 2050 relative to 2010 is highly unlikely. According to the International Energy Agency's (IEA) New Policies Scenario (2018a), the U.S. Energy Information Administration's Reference Case (Capuano 2018, 6) and a recent Resources for the Future Report (Newell et al. 2019), the dominance of fossil fuels in the energy mix will continue to increase to 2040 and likely beyond. This is driven by population increase and greater access to energy in developing countries, especially in Asia. It is also driven by an increase in oil and gas reserves due to new technology (shale revolution) and by countries that have fossil fuel reserves and rely heavily on export revenues to support their national development.

In scenarios P3 and P4, the increase in energy demand continues to 2050, and this is highly probable given the above discussion. To respond to an increase in energy demand by 2050 relative to 2010 (P3 and P4 scenarios) and still limit the increase to 1.5^{o}C, nuclear energy must increase between 468 to 501 per cent. Also, renewables should provide greater than 60 per cent of global electricity. Accordingly, non-biomass renewables must increase between 878 to 1,137 per cent and biomass renewables should increase between 121 to 418 per cent, with cumulative CCS (including BECCS) between 283 to 724 Gt CO_2 captured by 2100. This massive scale-up of several low-carbon technologies to displace fossil fuels in a relatively short period is unprecedented. If one considers that each of the mitigation pathways is far-fetched, then together they are especially unlikely. The rate and extent of the low carbon-emitting technologies to displace fossil fuels will be discussed in some detail in section 5.0 below.

5.0 POTENTIAL TECHNOLOGY PATHWAYS TO DISPLACE FOSSIL FUELS

5.1 NUCLEAR ENERGY

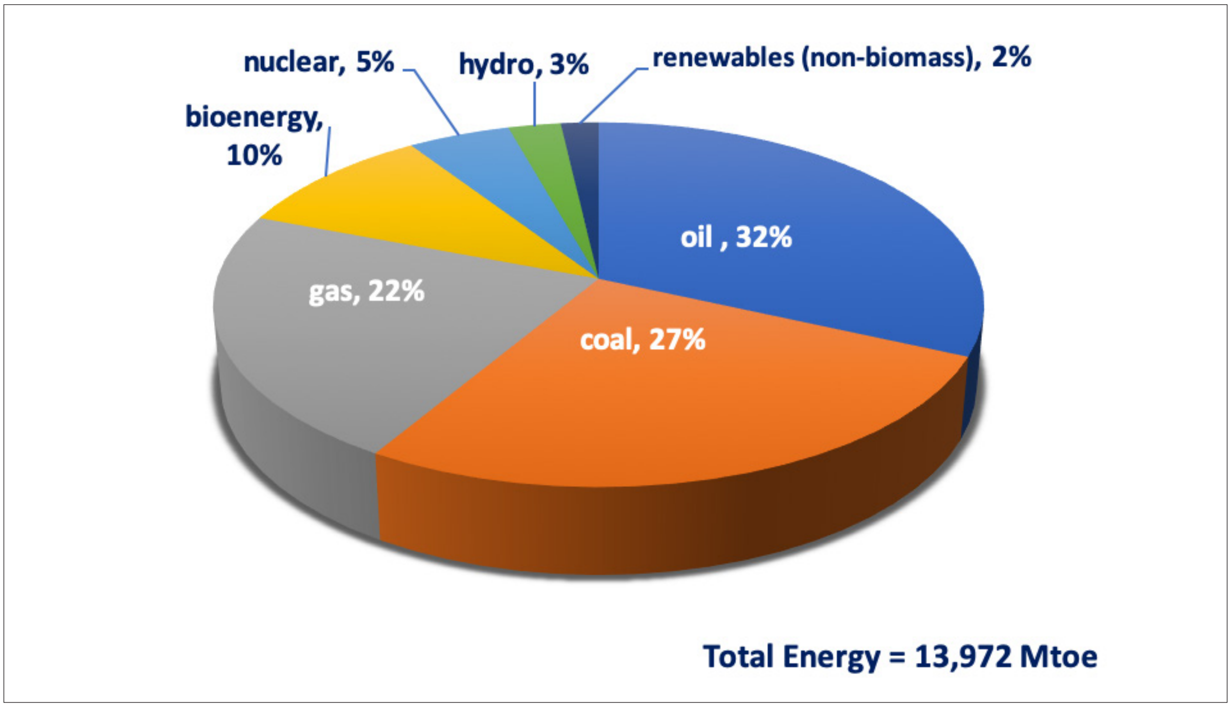
Arguments for and against nuclear energy have many dimensions. Nuclear energy's major advantage is its reliability, with near zero GHG emissions. As well, the high-energy density of its uranium fuel makes it far less land intensive than, for example, renewable energy and bioenergy. The challenges for building new nuclear plants have become formidable, including high capital costs in relation to natural gas plants and renewable energy, regulatory delays, technical hurdles associated with disposal of nuclear wastes, use of copious amounts of water for cooling, and political and societal concerns. Between 1996 and 2015, 80 new nuclear units came on line, mainly in developing countries, and these have been balanced by 75 plant retirements, mainly from developed countries (World Nuclear Association 2019). Currently, there are about 450 reactors operating worldwide, supplying 11 per cent of the world's electricity. While modest growth in nuclear energy is to be expected in developing countries, it is difficult to believe that there will be more than 2,000 reactors in operation by 2050. This is equivalent to building about one reactor every week between 2020 and 2050.

The development of small modular nuclear reactors and fusion energy shows promise as emerging and future forms of power that would generate electricity by using heat from nuclear fission and/or nuclear fusion reactions. The time to commercialization of these future energy sources, the likely cost of commercial plants and the scale required suggest that they will have little impact on displacing fossil fuel plants in the 2050 timeframe.

5.2 RENEWABLE ENERGY (NON-BIOMASS)

Wind and solar energy technologies have advanced rapidly and the costs of generating renewable electricity have fallen sharply in the last number of years. Along with hydroelectric power, they form most of the non-biomass renewable energy and include to a much lesser extent geothermal and ocean resources. As shown in Figure 1 (IEA 2018b), these combined sources of low-carbon electricity still account for only about five per cent of global energy on a million-tonnes-of-oil-equivalent basis (Mtoe) in 2017.

FIGURE 1 TOTAL GLOBAL ENERGY CONSUMPTION IN 2017



Source: IEA (2018b). In units of million tonnes of oil equivalent (Mtoe).

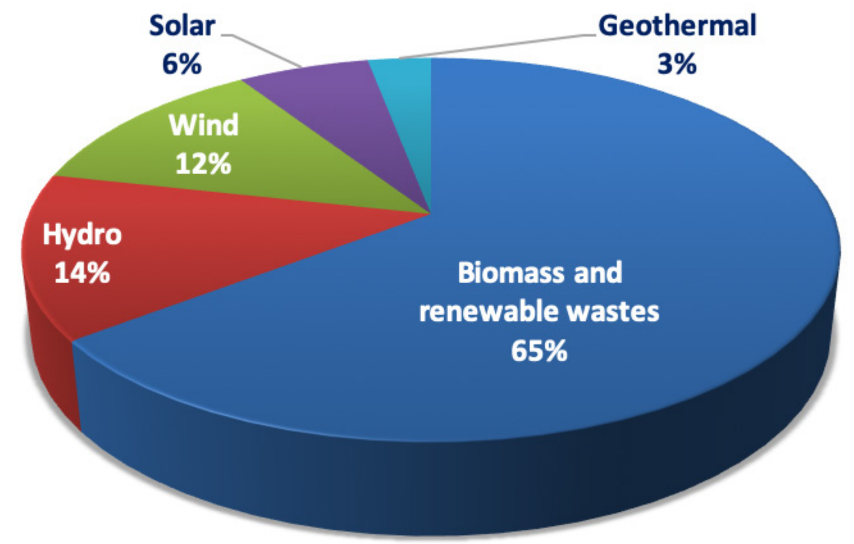
Assuming growth in the combined hydro and non-biomass renewables of about 800 per cent of 2017 figures by 2050 (P1 to P4 scenarios increase the range from 833 per cent to 1,327 per cent relative to 2010), this sector would exceed the current global total energy from oil. Although transformation of the global electricity sector is happening rapidly and there are excellent opportunities for increasing the portion of low-carbon renewable energy, it is questionable if the increase in renewables that meets IPCC targets can be achieved in the next 30 years. The main challenge with wind and solar is their inherently unreliable intermittent nature, requiring the rapid ramp-up of back-up power such as natural gas, hydro or batteries. They also require large amounts of land, which is unfavourable and potentially expensive at the scale required.

5.3 BIOENERGY

Bioenergy is considered a renewable energy resource derived from biomass that is sourced from forestry, agriculture and aquaculture operations. Woody biomass from forestry operations is by far the most common biomass available in Canada and worldwide. In Canada, bioenergy currently accounts for six per cent of total energy supply (Natural Resources Canada 2018). Ever since global warming became an issue, there has been a concerted global effort to increase supply from bioenergy, especially in countries that are concerned about energy security (i.e., bioethanol production in Brazil and the U.S.) and in those with considerable forestry resources (i.e., Nordic countries) that have traditionally used it for heat and power.

In the European Union (EU) countries, the renewable energy total of 211 million tonnes of oil equivalent (Mtoe) represented about 13 per cent of total energy production in 2015, of which biomass and waste generated about 65 per cent, as shown in Figure 2 (European Commission 2017, 43).

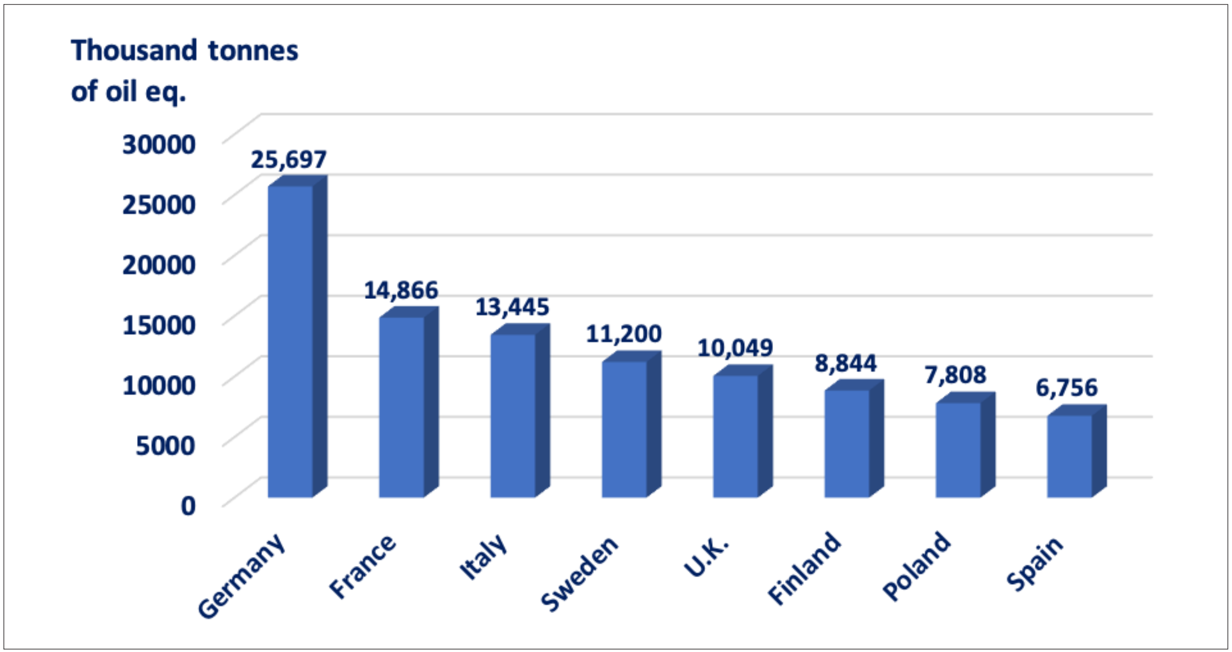
FIGURE 2 GROSS INLAND CONSUMPTION OF RENEWABLE ENERGY IN THE 28 EU COUNTRIES IN 2015



Source: European Commission (2017). In units of million tonnes of oil equivalent (Mtoe).

The consumption of biomass in the EU countries has increased by 65 per cent in the past 10 years (Eurostat 2019). The U.K. more than tripled its consumption between 2005 and 2015, primarily due to the conversion of coal plants to biomass-fired power generation. Figure 3 shows the top EU countries in relation to the consumption of biomass and renewable waste in 2015.

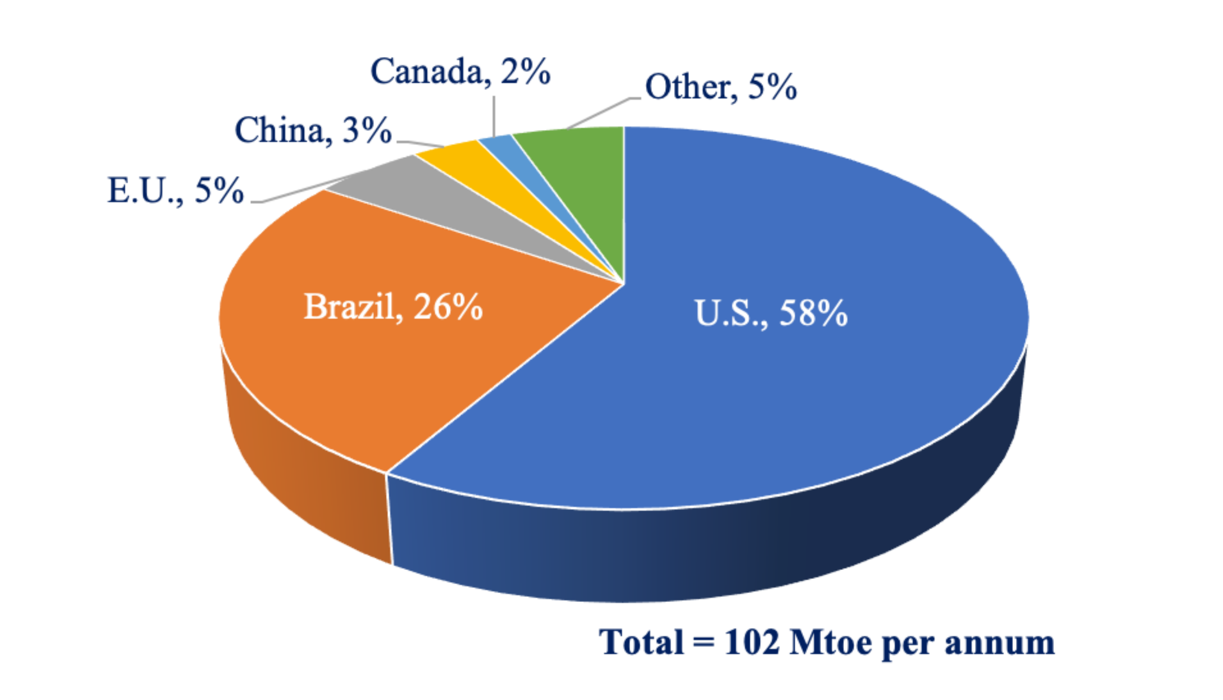
FIGURE 3 GROSS INLAND CONSUMPTION OF BIOMASS AND RENEWABLE WASTE IN THE TOP EU COUNTRIES IN 2015



Source: Eurostat (2019)

Global bioenergy production has also increased dramatically, more than doubling between 2007 and 2017. As shown in Figure 4, the U.S. produces over half of the world's ethanol and, together with Brazil, the two countries produce 85 per cent of the world's ethanol (Alternative Fuels Data Center 2018). The vast majority of U.S. ethanol is produced from corn, while Brazil primarily uses sugar cane. Canada produces about two per cent of global ethanol. Biodiesel from oil crops and hydrogenated vegetable oil has seen an average growth of around 2.5 per cent per year to reach 83 Mtoe (143 billion litres) in 2017, representing some eight per cent of all biofuels output (IEA 2019a). The demand for biofuels for use in vehicles and as a substitute for jet fuel is growing worldwide. This is due to policies primarily in the EU, U.S., China, India and Latin America that support sustainable development goals, and as a way of increasing shares of renewable energy.

FIGURE 4 WORLD ETHANOL PRODUCTION BY COUNTRY AND REGION IN 2017



Source: AFDC (2018). Units of million tonnes of oil equivalent (Mtoe) per annum.

The main case for renewable energy – when woody biomass is used for heat and electricity and biofuels are burned for transportation fuels – is that the CO_2 released is offset or partially offset by the CO_2 captured when trees are grown, or when feedstock crops are used to produce biofuels. Life cycle analyses used to rationalize these arguments maintain that even when considering the land-use change (such as deforestation and soil carbon changes) on the climate system, in general there is a reduction of GHG emissions when biofeedstocks are used compared to fossil fuels. Others have disputed these claims and have estimated that emissions due to land-use change for crop biofuels result in GHG emissions greater than those of fossil fuels except in the case of bio-waste products (Searchinger et al. 2008).

In the IPCC guidelines, direct CO_2 emissions from the combustion of biomass are recorded as zero in the energy sector and instead are reported in the Agriculture, Forestry and Other Land Use (AFOLU) sector of the inventory for the country where the biomass is produced (IPCC 2019). The IPCC does not consider biomass use carbon neutral and requires that estimates be made of emissions due to harvesting and regrowth, land-use changes caused by biomass production, use of fertilizers, processing of the feedstock, transportation of the fuel, and direct methane and nitrous oxide emissions from combustion reported in the energy sector. In our view, the IPCC accounting for biomass emissions is complex and impractical in that reported emissions by countries are nearly impossible to validate.

The IEA database of CO_2 emissions from fuel combustion excludes biomass fuels. The argument used is that there may not be net emissions if the biomass is sustainably produced and in situations where the rate of combustion is faster than annual regrowth.

Then, the net CO_2 emissions will appear as a loss of biomass stocks in the land-use change module.

Until a few years ago, the EU's CO_2 emissions from burning biomass or biofuels were counted as zero. This assumed that the biomass emissions were saved during the growth phase and accounted for in the land-use sector. The EU now acknowledges that this assumption is wrong and estimates that biomass emissions contributed an additional 90 to 150 million tonnes of CO_2e in 2013 to the EU emissions trading system (Bannon 2015).

Many scientists have concluded that policies which seek to replace fossil fuels with biomass energy systems appear to be misguided and risk making matters worse (Isaacs 2018). For example, a recent MIT-led study demonstrated that use of woody biomass in lieu of coal in power generation will worsen climate change impacts (Sterman et al. 2018). This is because of the time lag between the instantaneous CO_2 release from combustion of wood and the decades of regrowth required; the carbon debt was estimated to range between 44 and 104 years. In addition, there is a loss of future carbon sequestration from the growing trees that are cut down, a loss of soil carbon because of the disturbance, and a difference in carbon emissions due to the processing efficiency of biomass being less than that of coal.

It is our view that greenhouse gas emissions from all hydrocarbon sources, including biomass and biofuels, should be counted directly as emissions that contribute to exhausting the carbon budget[6] because global warming depends on the accumulated CO_2 emissions over the decades that they remain in the atmosphere. Accordingly, the scientifically allowable quantity of GHG emissions that can be emitted in total over a specified time to keep global warming at the desired temperature increase is dependent on the combustion step from all fuel sources and the concomitant atmospheric accumulation. Land-use change in the case of emissions from bioenergy is of much less importance.

The IPCC guidelines for bioenergy do not count the emissions going into the atmosphere. This contradicts the science that the emissions have a decades-long lifespan in the atmosphere regardless of the source of CO_2. Policies that have encouraged an upsurge in biomass and biofuel use as substitutes for fossil fuels are damaging to the global effort to reduce GHG emissions and to meeting obligations under the Paris Agreement. In reality, the emissions of many countries are at a significantly higher level than they have reported. The IPCC should take the biomass/biofuel pathway off the table and countries that have been the major devotees to this illusionary method for climate change mitigation should phase it out.

The benefits of biomass in contributing to carbon retention in, for example, forest growth and soil absorption should be positively considered in accounting for agriculture, forestry and land-use change (see section 5.6 below).

6 Carbon budgets are a way to measure the additional GHG emissions that can enter the atmosphere and still limit global warming to the desired levels. In the latest IPCC report (2018a,12), the remaining carbon budget was estimated at 420 $GtCO_2$ or about 10 years of current emissions with a 66-per-cent chance of avoiding a 1.5^{0}C increase.

5.4 NATURAL GAS AS A BRIDGE FUEL

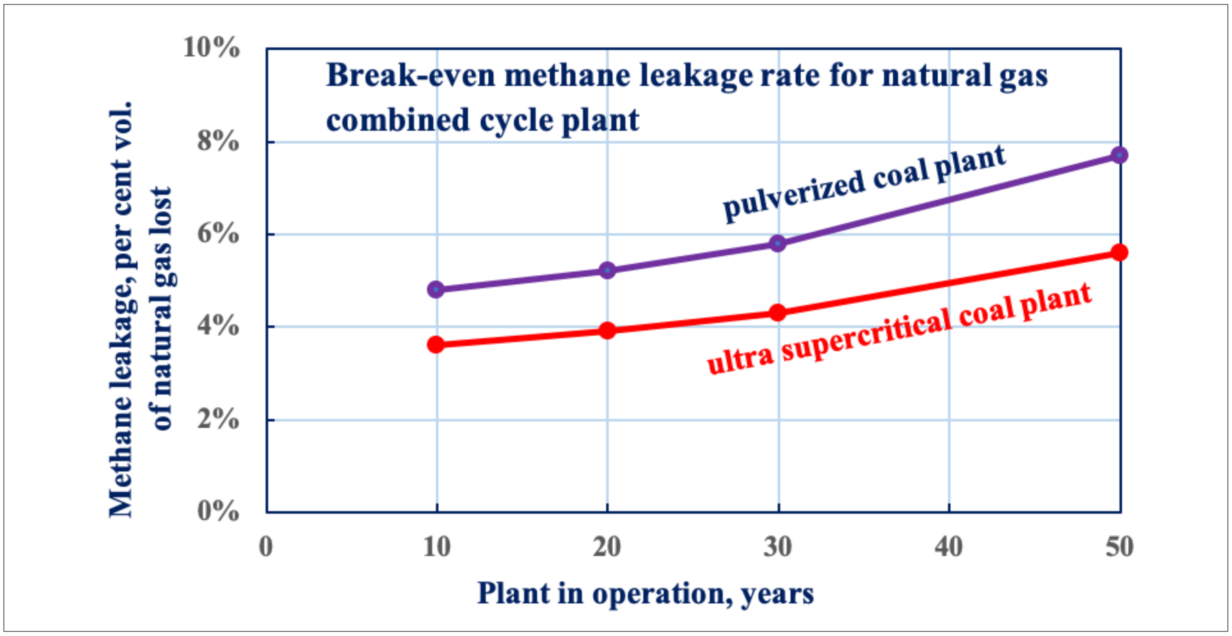
The global use of natural gas has grown significantly in the past decade and now makes up about a quarter of electric power generation (IEA 2019b). The growth is linked to its versatility as a clean burning fuel – a substitute for coal having about half of the GHG emissions of coal – and because natural gas generators can be ramped up and down quickly to support the integration of intermittent renewables. Natural gas growth has been especially strong in the United States and China. Growth in the U.S. is a result of natural gas being readily available and the low prices relative to the cost of generating electricity from coal (Logan et al. 2017). In China, burning natural gas instead of coal has helped reduce air pollution, thus providing public health benefits. With the advent of liquefied natural gas (LNG) – where natural gas is transported in liquid form in specially designed ships – natural gas is increasingly becoming a global commodity much like oil.

In the IPCC's scenarios P3 and P4 (Table 1), global natural gas demand increases by 21 per cent and 37 per cent respectively. This is consistent with the EIA's projection of a 40-per-cent increase by 2040 in their reference scenario (Capuano 2018).

While the environmental case for natural gas is strong, fugitive emissions due to leaks in the extraction, processing and transportation systems, and intentional venting are serious shortcomings. The climate benefits of switching from coal to natural gas supplies are negated at a leakage rate[7] of four per cent and higher, as shown in Figure 5 (Farquharson et al. 2016). The study compared the life cycle of coal and natural gas-based electricity and considered the 20 times higher warming potential of methane (the main component of natural gas) relative to CO_2. Estimates of a leakage rate from natural gas systems vary widely, but most studies suggest it ranges between one and five per cent and tends to the lower number (Farquharson et al. 2016, 858).

[7] Leakage rate is defined as the volumetric percentage of natural gas that is lost as methane through the entire natural gas system.

FIGURE 5 THE BREAK-EVEN METHANE LEAKAGE FOR A NATURAL GAS COMBINED CYCLE PLANT IN COMPARISON TO PULVERIZED COAL AND ULTRA SUPERCRITICAL COAL PLANT



Source: The figure was plotted from data provided by Farquharson et al. (2016).

There is now a strong effort in many countries to eliminate methane leaks from equipment, pneumatic devices, compressors, well completions and venting. For example, the Canadian government's regulations require a 40- to 45-per-cent methane reduction by 2025 to 2012 levels (Environment and Natural Resources Canada 2018).

5.5 CARBON CAPTURE UTILIZATION AND STORAGE (CCUS)

In three of the four scenarios (P2, P3 and P4), carbon capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS) feature prominently as necessary ways to limit temperature increase. The possibility of capturing and safely storing CO_2 geologically offers an important way to decouple fossil fuel and biofuel use from greenhouse gas emissions. An overview of the CCS technologies and the status of CCS projects are available in the literature (Leung et al. 2014; Global CCS Institute 2018).

CCS technologies have been in commercial use for natural gas processing since the 1920s and for enhanced oil recovery (EOR) since the 1970s. Using CCS for EOR is considered to negate any climate mitigation benefits due to the recovery of additional oil that would otherwise not be available. More recently, there have been commercial-scale projects where the captured CO_2 is stored in underground saline aquifers (Global CCS Institute 2019); for example:

- Sleipner in Norway is the world's first commercial CO_2 storage project. It has been operating since 1996, capturing the CO_2 from natural gas with a storage of about 0.9 Mt of CO_2 per annum;
- Shell Quest in Canada captures CO_2 from a steam methane reforming operation and stores about 1.2 CO_2 per annum; and

- Snohvit in Norway captures CO_2 from an LNG plant with storage of about 0.7 Mt of CO_2 per annum, also in saline formations.

The commercialization of CCS has proven much more difficult and slower than originally envisioned. In its monitoring of progress on ambitious clean energy goals, the IEA (2019c) shows that CCS is seriously off track. This is in part due to the parasitic consumption[8] contributing to the relatively high cost of CO_2 capture, the lack of infrastructure such as pipelines, uncertainty in the subsurface to prevent leakage, the sufficiency of storage space, legal and regulatory issues and, for bioenergy, the availability of land and feedstock at the scale required.

The scale of CCS required to achieve global warming goals is massive. For example, Shell (2018) scenarios for meeting the goals of the Paris Agreement envisage the building of some 10,000 large carbon capture and storage facilities by 2070. This is consistent with the above IPCC scenarios where the cumulative CO_2 that needs to be captured and stored to the year 2100 is between 348 and 1,191 Gt. It is important to appreciate that one Gt is equivalent to some 830 storage sites like Shell Quest and the displacing of some 320 coal-fired plants (500 MW) by zero-emissions electricity.

In the long run, CCS has a critical role to play in achieving the needed emission reductions, not only in fossil and biofuel combustion but also in the industrial sector where there are limited options for fuel switching.

In recent years, increasing attention has turned to using captured CO_2 as feedstock for valuable products such as concrete, plastics, fuels, carbon fibre and other useful materials. These CCUS technologies have the potential to reduce GHG emissions and generate positive economic returns. However, the CCUS industry is still young, and venture funding has only recently begun to come together. While many CCUS companies are at an active stage of research, some, like CarbonCure, a Canadian company that makes low-carbon concrete and whose products are used by over 100 concrete producers across North America, are commercial.

5.6 CARBON DIOXIDE REMOVAL AND NEGATIVE EMISSIONS

Technologies that produce energy from fossil fuels and/or biomass, while capturing and storing the resulting CO_2 emissions, have been discussed in terms of their readiness to proceed to numerous applications. Other mitigation options considered by the IPCC deploy negative emission technologies which remove CO_2 from the atmosphere and sequester it. These include direct air capture of CO_2, afforestation and reforestation,[9] and soil carbon retention.

Direct Air Capture (DAC): Refers to chemical processes that capture the CO_2 from ambient air and concentrate it, so that it can be injected into a storage reservoir or used to produce fuels. There are several DAC projects worldwide with most at an early stage

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8 The power and efficiency losses of energy input that is used to run the carbon capture unit. The typical level of parasitic consumption is estimated to range from 20 to 25 per cent.

9 Afforestation is the process of establishing forests in areas that have never been forested, while reforestation is the restoration of forests in areas where they were removed or destroyed.

of development or being tested at a demonstration scale. Because the concentration of CO_2 in the atmosphere is very low (about 410 PPM), considerably more energy is required than carbon capture from flue gas (CO_2 concentration of about five to 10 per cent or 50,000 to 100,000 PPM). Ranjan, Herzog and Meldon (2010) calculated that the energy cost of direct air capture, not including capital costs, would be in the range of $420-$630/tonnes of $CO_{2,}$ considering the minimum thermodynamic work required. This is in alignment with costs of $600/tonne of CO_2 reported by Climeworks, a leading DAC company (Evans 2017). A more recent study concluded that it would cost between $104 and $256 per tonne ($94 and $232 per ton) of captured CO_2 if existing technologies were implemented on a commercial scale (Keith et al. 2018). Nevertheless, the high carbon-free energy requirements will constrain the global growth of DAC and it is unlikely to have a large effect on CO_2 mitigation.

Afforestation and Reforestation: Planting trees is a powerful weapon for combating climate change. One estimate holds that it is possible to plant an additional 1.2 trillion trees in the world's parks, forests and abandoned land to compensate for 10 years of the global emissions of CO_2 (ETH Zurich 2019). The Shell (2018, 5) scenarios also emphasize the need to reforest an area the size of Brazil while achieving a net-zero deforestation. It appears that tree planting and much-reduced deforestation are effective ways of reducing atmospheric CO_2 emissions and need more attention from the IPCC. These methods should start to figure prominently in many countries' climate change strategies. Another form of mitigation is to sequester the carbon in long-lived forestry products, such as replacing steel and concrete with wood products or engineered wood products potentially containing nano-materials.

Soil Carbon Retention: Methods that involve using biological processes to increase carbon stocks in soils, forests and wetlands can remove CO_2 from the atmosphere. On a large scale, they can improve soil quality, local food security and biodiversity. Management practices such as reduced or no tillage, erosion control, use of cover crops and addition of organic amendments can significantly reduce carbon loss and increase carbon sequestration in the soil. The carbon sink capacity of soils is substantial, on the order of tens of gigatonnes of CO_2 (Lal 2004). The IPCC should quantify and promote soil carbon retention methods. Developed economies must advance the implementation of these methods while transferring the lessons and providing resources to developing countries.

6.0 CLIMATE MITIGATION STRATEGIES BY COUNTRIES

Global investment in energy infrastructure is a key indicator of the alignment with the Paris Agreement since investments made today will affect emissions for several decades. Between 2010 and 2018, global investment in renewable power was 40 per cent of total investment in the power sector (IEA 2019b). Global investment in upstream oil and gas infrastructure was about the same as the entire power sector. The U.S. and China represented over 50 per cent of the total global energy investment in 2018; their combined investment in renewable power significantly exceeded that of thermal power. However, the total combined investment of the U.S. and China in fossil fuel-based infrastructure (oil and gas and thermal power) exceeded the investment in renewable power by a margin of more than two to one. In Europe, total fossil fuel investment was about equal to that of renewable power. These current trends, alongside the analysis provided in Section 5.0, are an indication of the glaring mismatch with the paths required to meet the Paris Agreement in the next few decades.

A growing number of countries plan to ban the future sale of vehicles powered by fossil fuels, primarily gasoline and diesel (Worldatlas 2018). These include several EU countries, China, India and Japan. Like the shift to greater electrification of energy end uses in space and water heating, electrifying transportation will herald the potential for immense changes in the energy system driven by technology improvements and competitiveness. This indicates that many countries are aiming their policies at the changing energy market dynamics.

Some countries' carbon policies are designed to regulate specific industries such as transportation by banning fossil fuel-powered vehicles or power generation by shutting down coal-fired plants. Other countries are imposing a more encompassing carbon tax or cap-and-trade system to control emissions. The Canadian government has chosen to phase out coal-fired power generation by 2030 and levy a nation-wide carbon price on fuel combustion that does not include bioenergy fuels. The charge began at $20 in 2019 and will rise to $50 per tonne of CO_2 by 2022. Provinces could create their own systems of carbon pricing based on their needs. For provinces that did not create their own plans, the federal government imposed the tax to be redistributed to the provinces in a revenue-neutral manner. Dobson, Winter and Boyd (2019) give more details on how pricing coverage is applied across the economy, including exemptions to energy-intensive, trade-exposed industries.

In our view, carbon pricing should not be focused on revenue recycling; instead, the revenue should be invested in creative infrastructure solutions such as an east-to-west modern electric grid that would allow all provinces to develop more wind and solar opportunities. This could be a first step to the development of the proposed northern corridor as a means of enhancing and facilitating commerce, internal trade and a lower carbon footprint (Fellows and Tombe 2018).

A key conclusion from the analysis provided in this study is that the decarbonization pathways promoted by the IPCC and pursued by many developed countries are inadequate and mostly ineffective from the perspective of the scale required, the GHG emissions accounting system used and the accepted scientific basis for global warming. When it comes to biofuel energy policies, the accounting system is misguided. Many developed countries continue to use renewables as a cover for not properly accounting for combustion emissions from all fuels. As Le Quéré et al. (2019) report, policy-driven efforts in many countries to reduce emissions can be effective but need to be more stringent in line with the Paris Agreement. At the same time, there is a critical need to be wary of current policies that will increase emissions.

The world may or may not honour its pledge to keep temperatures below a certain level, but unless attention is paid to the GHG emissions that end up in the atmosphere, it will not matter if countries are developing the right strategies.

7.0 POLICY RECOMMENDATIONS

Through effective and innovative policies, Canada must manage the risks of global warming that bring on a wide range of costs due to forest fires, severe flooding and threats to infrastructure. Such policies need to consider that global GHG emissions continue to accumulate in the atmosphere and no significant reversal of this trend is indicated for the near future. The implication is that temperatures will continue to increase, if not accelerate, during this century. It is important that Canada build on its competitive advantage and pursue a distinct strategy from that of other countries in addressing climate change, including policies that:

- Direct[10] the IPCC to provide a more credible assessment to policy-makers on how fast and by how much emissions can be reduced and the degree of confidence in the solutions to global warming. Canada should stress the need for proper accounting for GHG emissions, especially in the case of bioenergy. This is required to ensure that the Paris Agreement is not jeopardized by unrealistic and unhelpful conjecture;
- Establish Canada as the first country in the world to extend carbon pricing to include direct emissions from bioenergy fuels. This will emphasize that the world should take seriously the need to curtail all GHG emissions based on scientific evidence and that all sectors of the economy must be treated alike;
- Take a more pro-active approach to adaptation and significantly increase investments in infrastructure to protect communities from the threat of sea-level rise and also those at risk from extreme weather events. Canada has little control over global emissions increasing in the atmosphere and the analysis in this paper suggests that temperatures in Canada will continue to rise. It is therefore prudent for Canada to focus resources on climate change initiatives that it can control. This is consistent with the recent report from the Council of Canadian Academies (Leggat, Beale and Gosselin 2019) that identified the climate change risks Canada should adapt to, and avoid major losses, damages and disruptions;
- Increase afforestation, reforestation and soil carbon enhancement while restricting land clearance to reduce heat-trapping emissions that cause global warming. Direct investments into non-combustion uses of biomass and fossil resources. As this analysis indicates, forest ecosystems and agricultural land can have a significant impact on climate change. For Canada, this would be part of a national strategy for a new non-combustion resource economy that includes a focus on research into innovative manufactured products such as carbon fibre and other low-carbon materials.

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10 Canada is a major financial contributor to the IPCC, as evidenced by the following quote from Environment and Climate Change Canada's website: "Canada also provides consistent financial support to the IPCC ($300,000/year) and ranks among the top 10 contributors to the IPCC's Trust Fund." Available at https://www.canada.ca/en/environment-climate-change/corporate/international-affairs/partnerships-organizations/intergovernmental-climate-change-panel.html

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