Low-Carbon Energy Futures: A Review of National Scenarios

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PROJET TROTTIER POUR L'AVENIR ÉNERGÉTIQUE

TROTTIER ENERGY FUTURES PROJECT

Low-Carbon Energy Futures: A Review of National Scenarios

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By Ralph D. Torrie, Tyler Bryant, Dale Marshall, Mitchell Beer, Blake Anderson, Ryan Kadowaki, and Johanne Whitmore

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Fondation familiale Trottier Family Foundation

David Suzuki Foundation
2211 West 4th Avenue, Suite 219
Vancouver, BC, Canada V6K 4S2
Tel 604.732.4228
www.davidsuzuki.ca

David Suzuki Foundation / Fondation David Suzuki

Canadian Academy of Engineering
180 Elgin St., Suite 1402
Ottawa, ON, Canada K2P 2K3
Tel 613.235.9056
www.acad-eng-gen.ca

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List of Abbreviations

€	Euro
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EIA	Energy Information Administration
FSC	Forestry Stewardship Council
GBP	Pounds Sterling
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GJ	Gigajoule
GW	Gigawatt
HVAC	Heating Ventilation and Air Conditioning
IT	Information Technology
IEA	International Energy Agency
kg	Kilogram
km	Kilometre
kW-h	Kilowatt Hour
Mt	Megatonne
PJ	Petajoule
PV	Photovoltaic
T & D	Transmission and Distribution
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
TWh	Terawatt Hour
UCA	United States, Canada, and Australia
USD	United States Dollar
VMT	Vehicle Miles Traveled

Preface

The Trottier Energy Futures Project (TEFP) is a research and modeling effort to determine how Canada can dramatically reduce its emissions of the greenhouse gas (GHG) emissions that are the primary cause of global climate change.

Established in 2010 as a partnership between the David Suzuki Foundation and the Canadian Academy of Engineering, the TEFP objective is to chart a course for an 80 per cent reduction in Canada's energy-related GHG emissions by 2050, using 1990 levels as a baseline.

As an early step in this wider effort, the Trottier Project has produced a series of background papers to shed light on the current state of knowledge on low-carbon energy futures. *Low-Carbon Energy Futures: A Review of National Scenarios* summarizes specific findings and broad themes from recent low-carbon energy scenarios produced for eight countries: Australia, the United States, Canada, Finland, France, Germany, Sweden, and the United Kingdom.

The other reports in the TEFP background paper series include:

- Canadian Greenhouse Gas Emissions – Current Patterns and Historical Trends
- An Inventory of Low-Carbon Energy for Canada
- Toward a Low-Carbon Future for Canada: Defining the Challenges

The final report of the Trottier Energy Futures Project will present scenarios of how Canada could make the transition to a sustainable, low-carbon energy (emissions 80% below current levels) future through increased efficiency, greater reliance on renewable and low-carbon fuels and electricity, and changes in the way we use energy.

Executive Summary

Eight recent low-carbon energy scenarios were selected for review by the Trottier Energy Futures Project to inform its effort to identify and analyze such scenarios for Canada. The criteria for inclusion in the review were that the scenario analyses be national in scope, comprehensive (covering all energy end uses), quantitative, long-term (to the year 2050), and focussed on deep reductions in greenhouse gas emissions (80 per cent below current levels). The studies selected were all conducted for rich, industrialized countries, namely Australia, the United States, Canada, Finland, France, Germany, Sweden, and the United Kingdom.

The studies reflect a variety of methods and a range of baseline demographic and economic outlooks. Long-term Gross Domestic Product (GDP) growth projections are in the range of 1.7 to 2.4 per cent per year, except for the German scenario, the only study that assumes negative population growth and a corresponding slower GDP growth of 1.1 per cent per year. Against these projected baselines, a variety of technologies and techniques are assessed for:

- Using fuel and electricity more efficiently
- Accelerating deployment of low-carbon energy supplies, and
- Deploying a variety of strategies to reduce the underlying demand for the energy services that give rise to the demand for fuels and electricity.

The studies all concluded, with varying degrees of substantiation and documentation, that deep reductions in greenhouse gas emissions are technologically feasible, and that the net costs and economic impacts of such a transition would be small compared to the baseline cost of the energy system and the overall projected size of the economy. Even countries with per capita GHG emissions far below Canada's were able to identify paths to a further 80 per cent reduction by 2050.

The scenario review reveals a number of common themes. They relate to the same four factors—efficiency, electrification, decarbonization, and biomass—that determine the level of energy-related greenhouse gas emissions in the eight studies, as well as a fifth key consideration: the level and pattern of energy services demand that represents the fundamental driver of demand for fuels and electricity:

- **Energy efficiency:** All the scenarios depend on significant energy efficiency gains across all sectors to achieve deep reductions in energy-related greenhouse gas emissions.
- **Renewable electricity:** The combination of increased electrification of energy end uses with the simultaneous decarbonization of the electricity supply is one of the defining features of low-carbon energy futures, and the renewable electricity technologies—hydroelectric, wind, geothermal, photovoltaic, biomass, wave, and tidal energy— play a central role in that decarbonization. Hydro and wind power are generally seen as having the greatest potential, but the U.S. study in particular shows very significant contributions from both solar photovoltaic and concentrated solar power plants.
- **Nuclear power:** The studies from France, Sweden, the UK, and the U.S. include scenario variations with a continued role for nuclear power. Those studies generally suggest a choice between reliance on nuclear and a shift towards energy efficiency and renewable energy, with some authors expressing a clear preference for efficiency and renewables.
- **Carbon capture and storage:** Carbon capture and storage (CCS) technology is included in several of the scenario variations. Due to uncertainties over cost and performance, CCS is generally treated as a contingency against the possibility that fossil fuel combustion cannot be phased out through efficiency and carbon-free alternatives.
- **Biomass:** Various forms of bioenergy are considered essential to achieving low-emission outcomes. In the low-carbon scenarios we reviewed, biomass provides 17 to 41 per cent of primary energy, despite significant trade-offs between food and fuel crops, as well as technical limitations on the quantity of bioenergy that can be sustainably produced.
- **Hydrogen:** Like electricity, hydrogen is an energy currency that emits no persistent greenhouse gas emissions at the point of end use, and can be produced from a variety of primary energy sources. There is still considerable uncertainty surrounding technologies and infrastructure in an energy future in which hydrogen plays a major

role, and additional research and innovation will be needed to reduce its cost relative to biofuels and electricity. Electrification, decarbonization, and biomass-based liquid and gaseous fuels crowd out hydrogen in the near to medium term in the scenarios we reviewed, but it does start to play a significant role in some of the studies in the latter part of the scenario period.

- **The fossil fuel industry:** Of all the countries included in this review, Canada is the only net exporter of petroleum. Even if domestic demand for fossil fuels (outside the fossil fuel industry itself) were reduced to zero, the country's petroleum production for world markets would still generate emissions that would make an 80 per cent greenhouse gas reduction for Canada impossible, at least with current oil and gas production technologies.
- **Energy services demand:** Several of the low-carbon scenarios include some degree of "what if" analysis to determine how changes in the level and pattern of energy services demand might affect GHG emissions. Factors such as economic structure, dwelling type and size, and changes in personal mobility demand are varied in a number of the studies.

The main low-carbon options are characterized by relatively high initial investments, followed by very low annual operating costs. Accordingly, the cost of low-carbon energy futures is sensitive to the cost of capital and the assumed lifetime of the investments, as well as the capital costs of actual efficiency and renewable energy technologies that have been declining rapidly in recent years. However, savings due to efficiency gains in low-carbon futures can actually exceed their levelized capital costs, which is calculated based on the capital cost, fuel cost, fixed and variable operating and maintenance costs, financing cost, and assumed utilization rate for an installed energy system. When efficiency savings exceed levelized capital costs, they deliver an indirect and positive economic impact. This significant potential to improve the efficiency of fuel and electricity use at low or even negative net cost is a major factor in assessing the net economic costs of a low-carbon transition. As a point of comparison, the future cost of fossil fuels is a factor in determining the cost and cost-effectiveness of low-carbon technology investments, and a key uncertainty in assessing the incremental economic impacts of low-carbon futures.

The magnitude of the transformation to a low-carbon future should not be underestimated. As the studies reviewed show, to achieve levels of energy efficiency and uptake of carbon-free fuel and electricity sufficient to reduce emissions to less than 20% of current levels by 2050, the absolute levels and rates of new technology deployment required are large compared to historical experience. Per capita energy use in the scenarios we reviewed is lower than it has been in 100 years in Canada. Building energy retrofits are deep and widespread. Renewable electricity technologies dominate electricity supply by 2050, and biomass-based fuels grow quickly to become the dominant source of liquid fuels for freight transportation and other applications where electrification is either not feasible or not affordable. Canada has access to the same technologies and techniques for efficiency and low-carbon energy development that are deployed in the scenarios we reviewed, but the country also faces unique challenges—in particular, the large portion of greenhouse gas emissions that result from the production of fossil fuels for export markets. Notwithstanding the extent of this transformation, the potential contributions to emission reductions from technologies and trends outside the energy system are generally not explored in depth in the scenarios we reviewed. The economy that generates energy services demand is about 20 times larger than the energy industry that provides the fuel and electricity, and trends and events in that larger economy that are not much influenced by fuel and electricity markets (eg. the invention of the Internet, an aging population, changing housing preferences) will continue to have profound implications for both the prospect and the economics of a low-carbon future. In the exploration of possible low-carbon, sustainable energy futures, these factors need to be considered alongside the efficiency and low-carbon supply options.

Avenirs énergétiques à faible intensité de carbone : Examen de scénarios nationaux

Préface

Le Projet Trottier pour l'avenir énergétique (PTAE) est un projet de recherche et de modélisation visant à déterminer comment le Canada pourrait réduire drastiquement ses émissions de gaz à effet de serre (GES), principale cause des changements climatiques mondiaux.

Un partenariat formé par la Fondation David Suzuki et l'Académie canadienne du génie a établi l'objectif premier du PTAE en 2010 : tracer la voie vers une réduction de 80 % des émissions de GES attribuables à la consommation d'énergie par rapport aux niveaux de 1990, année référence.

L'une des premières choses que le Projet Trottier a fait dans le cadre de cet effort a été de produire une série de documents d'information afin de jeter un éclairage sur l'état actuel des connaissances associées aux avenirs énergétiques sobres en carbone. Le document *Avenirs énergétiques à faible intensité carbonique : Examen de scénarios nationaux* résume certaines découvertes précises et plusieurs grands thèmes issus de scénarios énergétiques à faible intensité de carbone produits pour huit pays : l'Australie, les États-Unis, le Canada, la Finlande, la France, l'Allemagne, la Suède et le Royaume-Uni.

La série de documents d'information du PTAE comprend aussi les titres suivants (en anglais seulement) :

- Canadian Greenhouse Gas Emissions – Current Patterns and Historical Trends (Émissions canadiennes de gaz à effet de serre — Situation actuelle et tendances historiques)
- An Inventory of Low-Carbon Energy for Canada (Inventaire des sources d'énergie à faible intensité de carbone pour le Canada)
- Toward a Low-Carbon Future for Canada: Defining the Challenges (Vers un avenir à faible intensité de carbone au Canada : Cerner les défis)

Le rapport final du Projet Trottier pour l'avenir énergétique présentera des scénarios montrant comment le Canada pourrait devenir une économie durable et à faible intensité de carbone (émissions de 80 % inférieures aux niveaux actuels) grâce à une efficacité accrue, à une plus grande dépendance envers l'électricité et les combustibles renouvelables et à faible teneur en carbone, et à des changements dans la façon dont nous utilisons l'énergie.

Sommaire exécutif

Le Projet Trottier pour l'avenir énergétique a retenu, à des fins d'étude, huit récents scénarios énergétiques à faible intensité de carbone afin d'éclairer ses efforts visant à trouver des scénarios applicables au Canada et à les analyser. Pour faire partie de l'étude, les analyses de scénarios, en plus d'avoir une envergure nationale, doivent être complètes (englober toutes les utilisations finales de l'énergie), quantitatives, à long terme (pour l'année 2050) et fondées sur de profondes réductions des émissions de gaz à effet de serre (80 % inférieures aux niveaux actuels). Les études sélectionnées ont toutes été effectuées pour des pays riches et industrialisés, à savoir l'Australie, les États-Unis, le Canada, la Finlande, la France, l'Allemagne, la Suède et le Royaume-Uni

Les études témoignent d'un éventail de méthodes et de perspectives démographiques et économiques de base. Les projections de croissance à long terme du produit intérieur brut (PIB) sont de l'ordre de 1,7 à 2,4 % par an, sauf pour le scénario allemand, seule étude qui présume une croissance démographique négative et un ralentissement correspondant de la croissance du PIB de 1,1 % par an. En fonction de ces conditions de base, une panoplie de techniques et de technologies sont évaluées aux fins suivantes :

- Faire un usage plus efficace des combustibles et de l'électricité;
- Accélérer le déploiement des approvisionnements énergétiques à faible intensité de carbone;
- Déployer un éventail de stratégies visant à réduire la demande sous-jacente de services énergétiques, laquelle stimule la demande de combustibles et d'électricité.

Les études ont toutes conclu, avec divers degrés de justification et de documentation, qu'il est technologiquement possible de réduire considérablement les émissions de gaz à effet de serre et que les coûts nets et les répercussions économiques d'une telle transition seraient faibles comparativement aux coûts de base du système énergétique et de la taille prévue de l'économie. Même les pays dont les émissions de GES par habitant sont largement inférieures à celles du Canada ont été en mesure de trouver des pistes devant mener à une réduction supplémentaire de 80 % d'ici 2050.

L'examen des scénarios révèle un certain nombre de thèmes communs. Ces thèmes concernent les quatre mêmes facteurs (l'efficacité, l'électrification, la décarbonisation et la biomasse) qui déterminent dans les huit études le niveau d'émissions de gaz à effet de serre liées à la consommation d'énergie, en plus d'un cinquième facteur essentiel : l'importance de la demande de services énergétiques, force motrice de la demande de combustibles et d'électricité, ainsi que les tendances qui caractérisent cette demande :

- **Efficacité énergétique :** Tous les scénarios reposent sur des gains d'efficacité énergétique considérables dans tous les secteurs afin de réaliser de profondes réductions des émissions de gaz à effet de serre attribuables à la consommation d'énergie.
- **Électricité renouvelable :** La combinaison de l'électrification accrue des utilisations finales de l'énergie et de la décarbonisation simultanée de l'approvisionnement en électricité est l'une des caractéristiques déterminantes d'un avenir à faible intensité de carbone. Les technologies associées à l'électricité renouvelable — qu'elles soient hydroélectrique, éolienne, géothermique, photovoltaïque, issue de la biomasse, produite par les vagues ou marémotrice — jouent un rôle central dans cette décarbonisation. L'énergie éolienne et hydraulique est généralement considérée comme ayant le plus grand potentiel, mais l'étude américaine, en particulier, montre une contribution très importante des centrales solaires et photovoltaïques.
- **Énergie nucléaire :** Les études de la France, de la Suède, du Royaume-Uni et des États-Unis recèlent de variantes de scénarios où l'énergie nucléaire est présente. En général, ces études évoquent un choix entre le recours au nucléaire et une réorientation vers l'efficacité énergétique et les énergies renouvelables, quelques auteurs exprimant une nette préférence pour l'efficacité et les énergies renouvelables.
- **Captage et stockage du carbone :** La technologie de captage et stockage du carbone (CSC) fait partie de plusieurs variantes de scénarios. En raison des incertitudes relatives à son coût et son rendement, le CSC est généralement considéré comme une éventualité à envisager si jamais les gains en efficacité et les solutions de rechange sans carbone n'arrivaient pas à éliminer progressivement la combustion de combustibles fossiles.
- **Biomasse :** Diverses formes de bioénergie sont considérées comme essentielles à l'atteinte de résultats à faible émission de carbone. En effet, dans les scénarios à faible intensité de carbone que nous avons examinés, la biomasse fournit de 17 à 41 % de l'énergie primaire, malgré d'importants compromis entre les cultures alimentaires et les cultures énergétiques, ainsi que les limitations techniques à la quantité de bioénergie qu'on peut produire de manière durable.
- **Hydrogène :** Comme l'électricité, l'hydrogène est une monnaie énergétique qui n'émet pas de gaz à effet de serre persistants au stade de l'emploi final, et qui peut être produite à partir d'un éventail de sources d'énergie primaire. Il y a encore beaucoup d'incertitude au sujet des technologies et des infrastructures qui seraient nécessaires dans un avenir énergétique où l'hydrogène jouerait un rôle majeur; il faudra faire des recherches et des innovations supplémentaires pour réduire son coût par rapport aux biocarburants et à l'électricité. L'électrification, la décarbonisation et les liquides et combustibles gazeux à base de biomasse remplacent l'hydrogène à court ou moyen termes dans les scénarios que nous avons examinés, mais l'hydrogène commence à jouer un rôle important dans certains des scénarios étudiés à la dernière partie.
- **Industrie des combustibles fossiles :** De tous les pays traités dans cette étude, le Canada est le seul exportateur net de pétrole. Même si la demande intérieure de combustibles fossiles (en dehors de l'industrie des combustibles fossiles elle-même) était réduite à zéro, la production pétrolière que le pays envoie sur les marchés mondiaux générerait quand même des émissions qui rendraient impossible une réduction de 80 % des émissions de gaz à effet de serre au Canada, du moins compte tenu des technologies actuellement employées dans la production gazière et pétrolière.
- **Demande de services énergétiques :** Plusieurs scénarios à faible intensité de carbone comprennent un certain degré d'analyses fondées sur des simulations afin de déterminer comment les variations d'intensité et les

tendances changeantes de la demande de services énergétiques pourraient influer sur les émissions de GES. Il s'agit notamment de la structure économique, du type d'habitation et des dimensions de celles-ci, ou encore des changements en matière de mobilité personnelle.

Les principales solutions à faible intensité de carbone se caractérisent par des investissements initiaux relativement élevés, suivis par de très faibles coûts d'exploitation annuels. Par conséquent, le coût d'un avenir énergétique à faible intensité de carbone dépend du coût du capital et de la durée de vie présumée des investissements, ainsi que des coûts d'investissements des technologies d'efficacité énergétique et d'énergie renouvelable, qui baissent rapidement depuis quelques années. Cependant, les économies attribuables aux gains d'efficacité réalisés dans un avenir à faible intensité de carbone peuvent en fait dépasser leurs coûts d'investissements actualisés, qui sont calculés en fonction des coûts afférents au capital, au combustible, à l'entretien et l'exploitation (fixes ou variables), et au financement, en plus du taux d'utilisation présumé d'un système énergétique mis en place. Lorsque les économies d'énergie engendrées par les gains d'efficacité dépassent les coûts d'investissements actualisés, elles produisent une incidence économique indirecte et positive. Ce grand potentiel d'améliorer l'efficacité de la consommation de combustible et d'électricité à un coût net faible, voire négatif, est un facteur important dans l'évaluation des coûts économiques nets de la transition à une économie à faible intensité de carbone. Comme point de comparaison, le coût futur des combustibles fossiles est un facteur dont il faut tenir compte pour déterminer le coût et la rentabilité des investissements dans les technologies à faible émission de carbone; ce coût constitue également une incertitude majeure dans l'évaluation des effets économiques différentiels d'un avenir à faible intensité de carbone.

Il ne faut pas sous-estimer l'ampleur du passage à un avenir à faible intensité de carbone. En effet, comme le montrent les études consultées, il faut que les taux absolus de déploiement des nouvelles technologies soient élevés par rapport aux expériences passées pour atteindre des niveaux d'efficacité énergétique et de biomobilisation d'électricité et de combustible sans carbone suffisants pour réduire les émissions à moins de 20 % des niveaux actuels d'ici 2050. Dans les scénarios que nous avons examinés, la consommation d'énergie par habitant est inférieure à ce qu'elle est depuis 100 ans au Canada. Le rendement énergétique des bâtiments s'est considérablement amélioré. Les techniques de production d'électricité à partir de sources d'énergie renouvelables dominent l'approvisionnement en électricité d'ici 2050, alors que les biocombustibles gagnent rapidement en popularité pour devenir la principale source de combustibles liquides dans le secteur du transport de marchandises, ainsi que dans d'autres applications où l'électrification est soit impossible soit hors de prix. Le Canada a accès aux mêmes techniques et technologies qui permettent d'accroître l'efficacité et de développer l'énergie à faible intensité de carbone dans les scénarios que nous avons examinés, mais le pays est aussi confronté à des défis uniques — en particulier, la proportion importante des émissions de gaz à effet de serre issues de la production de combustibles fossiles destinés aux marchés d'exportation. Malgré l'ampleur de cette transformation, les contributions potentielles des technologies et des tendances extérieures au système à la réduction des émissions ne sont généralement pas étudiées en profondeur dans les scénarios que nous avons examinés. L'économie qui génère la demande de services énergétiques est environ 20 fois supérieure à l'industrie énergétique qui fournit le combustible et l'électricité; les tendances et événements qui subissent peu l'influence des marchés du combustible et de l'électricité (par exemple, l'invention de l'Internet, le vieillissement de la population, l'évolution des préférences en matière de logement) auront toujours des répercussions profondes sur la perspective et les fondements économiques d'un avenir à faible intensité de carbone. Il faut donc tenir compte de ces facteurs en plus des solutions d'efficacité et d'approvisionnement à faible intensité de carbone lorsqu'on étudie d'éventuelles perspectives fondées sur l'énergie renouvelable et sur une faible intensité carbone.

Introduction and Selection of Studies for Review

The objective of the Trottier Energy Futures Project is to determine what a sustainable, low-carbon energy future (emissions 80 per cent below 1990 levels) might look like for Canada, including the implementation pathways that could lead us there by 2050. Our research into this question included a review of eight national efforts to think rigorously and quantitatively about futures in which greenhouse gas (GHG) emissions are reduced to this extent.

In selecting studies for detailed review, we sought energy futures scenarios that:

- Were carried out in wealthy, industrialized, largely urbanized countries like Canada, with modern fossil fuel and electricity-based energy systems and well-developed building, transportation, and industrial infrastructure
- Were national in scope
- Included at least one long-range (to 2050 or beyond), low-carbon (minimum 80 per cent below base year) scenario
- Were comprehensive, covering all economic sectors and all fuels
- Were based on quantitative analysis that was well enough documented to permit comparisons with scenarios from other countries
- Placed their low-carbon scenario analysis in the context of other desirable features of a future energy system, such as resilience, sustainability, and economic efficiency.

There are only a few efforts that satisfy these criteria, almost all of them produced in the last 10 years.[1] The studies selected for this review are a sample of the most recent country-specific research efforts available. Most work on carbon reduction scenarios prior to 2000 considered whether emissions could be reduced at all, or brought down by five to 20 per cent on a 2020 time scale, perhaps ultimately by 30 to 50 per cent, but not by 80 per cent. We scanned the literature and communicated with colleagues in the low-carbon research world to identify who was doing what where, and Appendix 2 includes references to many low-carbon studies that we considered in our initial survey but did not include in our more detailed review.

Compared to the early climate change response literature, the search for an 80 per cent emission reduction pathway (the magnitude of the response required to avoid what many scientists refer to as dangerous climate change) requires a deeper, broader strategy for transforming the energy system. When we add to that objective the caveat that emission reductions must also satisfy the imperatives of sustainability, the effort becomes even more challenging, and even more transformative.

The eight studies included in this review reflect a range of perspectives and methods to achieve a low-carbon energy system (although most of the studies are grounded in technological solutions). They are all from industrialized economies, and from jurisdictions that have significant features in common with Canada (climate or industrial structure, technological infrastructure, or cultural and political traditions).

The countries for which the scenarios were developed include Australia, Canada, Finland, France, Germany, Sweden, the United Kingdom, and the United States. The studies are listed in Table 1, along with short-form citations that we use for reference throughout this report. Several of the studies included multiple scenarios, so where applicable, the table indicates the specific scenario used for the inter-country comparisons found later in this report.[2]

1 Appendix 2 contains a list of low-carbon studies that were reviewed during the writing of this report, but did not meet these specific criteria.

2 For studies with multiple scenarios, there were no strict criteria for selecting the one we used for the quantitative inter-study comparisons. In general, we opted for mid-range scenarios that contained a balanced mix of low-carbon solutions.

Table 1. Low-Carbon Scenario Analyses Included in Review

Criteria	Short-Form Citation	Full Reference	Scenario	Base Year	Target Year	Reduction in GHG Emissions	Estimated Emissions in 2050 (Mt CO2e)	Coverage
Australia	AI 2002	Hal Turton, Jinlong Ma, Hugh Saddler and Clive Hamilton, "Long-Term Greenhouse Gas Scenarios: A Pilot Study of How Australia Can Achieve Deep Cuts in Emissions", Discussion Paper No. 48, The Australia Institute, October 2002.	Not Applicable	1999	2050	60% below 1999 levels by 2050	106	Energy, agriculture, forestry, land-use change
Canada	GP/EREC 2010	Sven Teske and Christine Lins. Energy (R)evolution: A Sustainable Energy Outlook for Canada. Greenpeace and European Renewable Energy Council (EREC), August, 2010.	energy r[e] volution	2007	2050	94% below 1990 levels by 2050	29	All energy-related GHGs
United States[3]	RMI 2011	Amory B. Lovins and Rocky Mountain Institute. Reinventing Fire: Bold Business Solutions for the New Energy Era. Vermont: Chelsea Green Publishing, 2011.	Transform	2000	2050	81% below 2000 levels by 2050	800	Industry, transportation, buildings, energy, electricity
Finland	FPMO	Finland Prime Minister's Office, "Government Foresight Report on Long-term Climate and Energy Policy: Towards a Low Carbon Finland", Prime Minister's Office Publications 30/2009, Helsinki, 2009.	Sustainable Daily Mile	2007	2050	80% below 1990 levels by 2050	7.1	All sectors, emphasis on energy

3 Jeffery Greenblatt and Jane Long, *California's Energy Future: The View to 2050* (San Francisco: Council on Science and Technology, 2011) was also reviewed for the United States, and a summary can be found in Appendix 1. Despite being a comprehensive analysis, the Californian report was omitted because it is not a nation study. Amory Lovins and Rocky Mountain Institute, Reinventing Fire: Bold Business Solutions for the New Energy Era (Vermont: Chelsea Green Publishing, 2011) provides a wider view of the entire U.S. economy, and is therefore the country's main contribution to our comparison.

Criteria	Short-Form Citation	Full Reference	Scenario	Base Year	Target Year	Reduction in GHG Emissions	Estimated Emissions in 2050 (Mt CO2e)	Coverage
France	AEME 2004	Pierre Radanne, "La division par 4 des émissions de dioxide de carbone en France d'ici 2050: Introduction au débat", Agence de l'environnement et de la maîtrise de l'énergie, March 2004.	F4 RCogN	2000	2050	75% below 2000 levels by 2050	32	Steel, other industry, residential, tertiary, agriculture, transportation
Germany	BMU 2008	Joachim Nitsch, "Further Development of the "Strategy to Increase the Use of Renewable Energies" Within the Context of the Current Climate Protection Goals of Germany and Europe", study commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (9BMU), October 2008.	Lead Scenario 2008	2005	2050	78.5% below 1990 levels by 2050	21	Energy-related+blast furnace process GHG
Sweden	IVL 2010	Jenny Gode, Eric Särnholm, Lars Zetterberg, Jenny Arnell, Therese Zetterberg, "Swedish Long-Term Low Carbon Scenario: Exploratory Study of Opportunities and Barriers", IVL Swedish Environment Research Institute Report B1955.	Not Applicable	2005	2050	79% below 2005 level by 2050	12	Industry, residential and service sectors, transport, electricity, district heating, fuels (including forest fuels)
United Kingdom	EKERC 2009	Jim Skea, Paul Ekins and Mark Winskel, Energy 2050: Making the Transition to a Secure Low Carbon Energy System, Earthscan, London, 2011.	LC	2000	2050	80% below 1990 levels by 2050	119	All sectors

Setting the Stage – Country Profiles

To facilitate comparisons among countries, we compiled a number of indicators from the International Energy Agency (IEA) database and summarized them in Table 2. The selected studies use different base years for their analyses, and also employ slightly different conventions for defining terms such as primary energy and energy-related emissions. By using the IEA database for an initial profile, we can focus on a single common year (2009) and ensure internal consistency of the comparisons.

Table 2. Selected Country Indicators[4]

	Australia	Canada	USA	Finland	France	Germany	Sweden	UK
Population in 2009, millions	22.1	33.74	307.48	5.34	64.49	81.88	9.3	61.79
Annual growth rate, 1990-2009	0.7%	0.5%	0.5%	0.2%	0.3%	0.0%	0.3%	0.3%
GDP in 2009, in billion 2000 USD	535	846	11,357	141	1,473	1,999	286	1,677
Annual growth rate, 1990-2009	1.5%	1.0%	0.9%	0.9%	0.6%	0.5%	1.1%	0.7%
Total Primary Energy Supply (TPES), in PJ in 2009	5,488	10,639	90,557	1,389	10,727	13,336	1,901	8,238
Annual growth rate, 1990-2009	0.8%	0.1%	-0.1%	0.5%	0.3%	-0.1%	0.3%	-0.5%
Total Final Consumption (TFC), in PJ in 2009[5]	3,254	8,130	61,233	1,021	6,710	9,375	1,339	5,532
Of which non-energy uses constitute:	5.0%	10.4%	8.9%	5.7%	7.4%	10.0%	5.2%	6.1%
Annual growth rate of TFC, 1990-2009	1.7%	1.1%	0.6%	0.5%	0.6%	-0.4%	0.0%	-0.2%
Energy-Related GHG Emissions, in MtCO2e, in 2009[6]	395	521	5,195	55	354	750	42	466
Annual growth rate, 1990-2009	2.2%	1.0%	0.3%	0.1%	0.0%	-1.2%	-1.2%	-0.9%

4 Except for CO2 emissions (see note 6), data in this table are taken from International Energy Agency, *Energy Balance for OECD Countries* (Paris: 2011). The most recent complete data set in the report is for 2009.

5 The Total Final Consumption (TFC) shown here includes non-energy use, as does the calculated growth rate for TFC from 1990-2009. The non-energy share of TFC includes petrochemical feedstocks, lubricants, and other non-combustion applications.

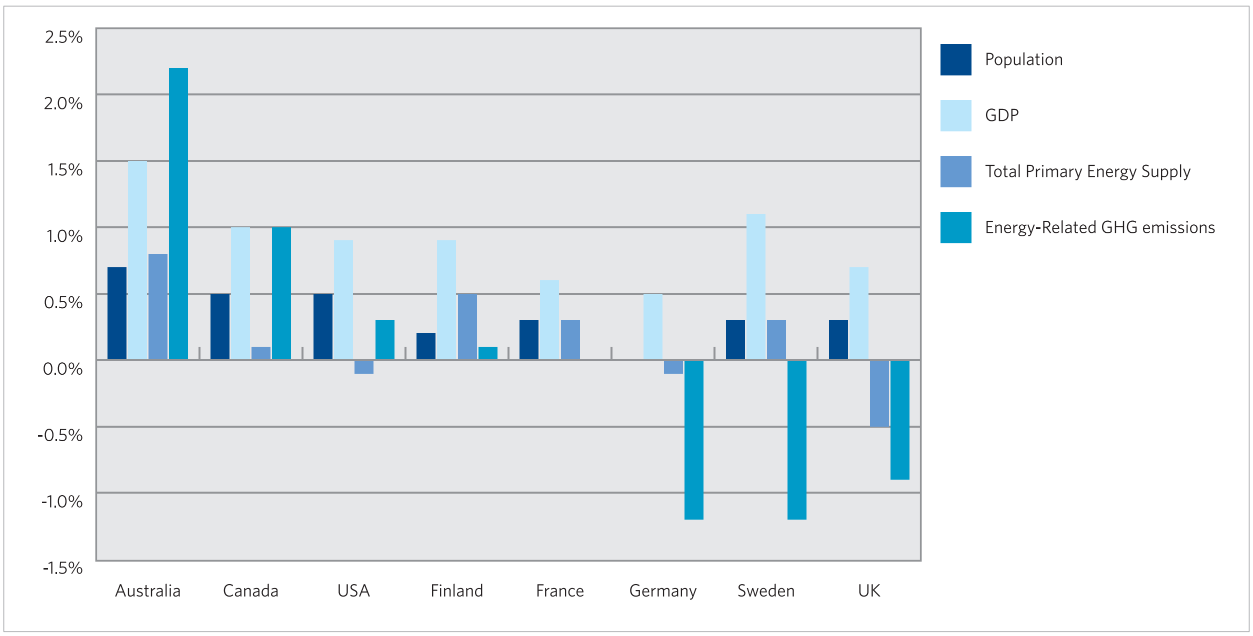
6 Emissions data are taken from International Energy Agency, *CO2 Emissions from Fuel Combustion* (Paris: 2011). Data in the table are for 2009 and include emissions from combustion only. Additional energy-related emissions, primarily fugitive emissions associated with fossil fuel production, refining, and delivery, are also reported only up to 2008. Fugitive emissions, expressed as CO2e, would increase the totals in this table by 5 to 12 per cent depending on the country. Escalating the 2008 fugitive emissions by the 2008-2009 year-over-year growth in combustion-related emissions yields estimated 2009 fugitive emissions of 47 Mt for Australia, 51 Mt for Canada, 364 Mt for the USA, 2 Mt for Finland, 28 Mt for France, 48 Mt for Germany, 2 Mt for Sweden, and 38 Mt for the UK.

While all the countries included in Table 2 have high-income, industrialized economies, their recent population, energy use and greenhouse gas emissions histories are quite different. Figure 1 shows a clear distinction between the "old world" and the "new world" in both population and GHG growth.

- Over the past 20 years, population growth in the European countries has averaged 0.0-0.3 per cent per year, compared to 0.5-0.7 per cent averages in the United States, Canada and Australia ("UCA" in this discussion). Historical growth rates in greenhouse gas emissions also show a clear differentiation between the European countries and the UCA group.

- In the European countries considered in this review, energy-related greenhouse gas emissions have been virtually flat (Finland, France) or declining (Germany, Sweden, and the UK) since 1990, in contrast to the positive (but declining) annual growth rates in Australia (2.2 per cent), Canada (1 per cent), and the United States (0.3 per cent).

Figure 1. Selected Country Indicators (Growth Rates 1990-2009)



- There is no clear coupling of GDP and greenhouse gas emissions growth in either the European or the UCA groups, but the extent of the decoupling is especially notable in the European countries. In Sweden, for example, economic growth has averaged 1.1 per cent per year, while emissions have declined by 1.2 per cent per year.

For further points of comparison between the countries, Table 3 and Table 4 show a series of intensity and per capita indicators of energy and emissions activity from the IEA database. The data confirm that these are all highly developed economies with per capita GDP in the range of USD 23,000 to 37,000 and total final consumption of fuels and electricity in the range of 100-240 GJ per capita. All the countries have a relatively high reliance on electricity (19 to 33 per cent of final energy use), and nuclear power contributes to the electricity supply in all but one (Australia).

The indicators in Table 3 illustrate how circumstances in the countries differ on key issues that are important to their energy systems and climate change response options.

Notably, per capita greenhouse gas emissions, which depend on both per capita energy use and the carbon intensity of the energy mix, are much higher for the UCA group than for the European countries. Per capita energy use is lower in Europe than in the UCA group, reflecting more compact urban forms, a more fuel-efficient vehicle fleet, less energy-intensive industrial activity (reflected in the TFC/GDP ratio), and more energy-efficient infrastructure and technology. Finland is an exception to the general rule in Europe, with relatively high per capita TFC (191 GJ) and TFC per GDP (7.2 GJ per thousand 2000USD) that reflect the prevalence of the country's energy-intensive paper and primary metals industries.

Table 3. Selected Energy and Emissions Indicators (all data for 2009)

	Australia	Canada	USA	Finland	France	Germany	Sweden	UK
Emissions/capita (tonnes CO2e)	17.9	15.4	16.9	10.3	5.5	9.2	4.5	7.5
Change from 1990-2009	33%	9%	-2%	-2%	-5%	-20%	-24%	-20%
GDP per capita, (thousands 2000 USD)	24.2	25.1	36.9	26.4	22.8	24.4	30.8	27.1
Change from 1990-2009	14%	6%	5%	12%	4%	6%	11%	8%
TFC/capita, in GJ/capita	140	216	181	180	96	103	137	84
Change from 1990-2009	14%	0%	-6%	0%	-3%	-1%	-1%	-1%
TFC/GDP, (GJ/thousand 2000 USD)[7]	5.8	8.6	4.9	6.8	4.2	4.2	4.4	3.1
Change from 1990-2009	1%	-6%	-10%	-11%	-7%	-21%	-19%	-21%
Emissions/TFC, (kg CO2e/GJ)	127.7	71.5	93.1	57.1	57.0	88.9	32.8	89.7
Change from 1990-2009	16%	10%	4%	-2%	-3%	-6%	-16%	-6%

The carbon intensity of energy consumption (in kg CO2e/GJ) does not show the same clear division between Europe and the UCA group.[8] Sweden has by far the lowest overall carbon intensity, at only 33 kg CO2e per GJ, reflecting the very high percentage of its electricity supply that comes from carbon-free sources—hydro, biomass, and nuclear power—as well as the high level of biomass use by industry, particularly pulp and paper. At the other end of the scale, at 128 kg CO2e per GJ,

7 In this table, the TFC data used are net of non-energy uses, as shown in the final row, slightly lower than the values used in Table 2.

8 In the International Energy Agency, Energy Balances of OECD Countries, total final consumption (TFC)—called secondary energy in some data systems—refers to the fuels and electricity used at the point of end use. Total primary energy supply (TPES) includes total final consumption plus all the energy used to produce, refine, and deliver the TFC to final consumers. The biggest contributors to the difference between primary and final energy are the energy losses associated with nuclear and thermal power plants, where up to two-thirds of the heat generated may be rejected as waste heat, but primary energy also includes electricity transmission and distribution (T & D) losses, conversion losses in the production of biogas and biofuels from primary biomass, and the energy consumption of the fossil fuel industry itself.

In practice, primary energy is defined in a variety of different ways. While power plant and T & D losses are almost always included, the energy use of the fossil fuel and pipeline industry is sometimes wholly or partly counted as final consumption.

There are also different conventions for counting the primary energy from hydroelectric, wind, photovoltaic, and other renewable primary electricity sources, as well as from nuclear plants. In the IEA database on which Table 2, Table 3, and Table 4 are based, heat generation is used to measure the primary energy from nuclear, geothermal, and solar thermal power generation systems, while electricity production is counted as primary for solar photovoltaic, wind, hydro, tidal, and wave energy. In calculating the primary energy content of nuclear, the convention used is to estimate the primary heat generation by assuming power is produced at 33 per cent efficiency.

the carbon intensity of energy in Australia is four times higher, reflecting its dependence on high-carbon coal for power production. Like Sweden, Canada generates a large share of its electricity supply from carbon-free sources, but Canada's overall carbon intensity is still twice that of Sweden, reflecting much lower contributions from renewable sources and nuclear in the primary energy mix, as well as continued reliance on coal in some parts of the country.

It is interesting to look at the factors at play for the two countries with the lowest per capita GHG emissions—France, at 5.5 tonnes CO2e, and Sweden, at 4.5 tonnes CO2e. Sweden has significantly higher per capita GDP than France, as well as higher per capita energy use, yet its per capita GHG emissions are still 20 per cent lower than France's. Table 4 shows that both countries derive a significant portion of their electricity from nuclear (76 per cent for France, 38 per cent for Sweden), but Sweden generates 58 per cent of its supply from renewables (hydro, biomass), compared to only 13 per cent for France. Sweden has also gone further than any of the other countries in electrifying energy use, with fully 33 per cent of end use energy provided by electricity, compared to 23 per cent for France.

Table 4. Selected Energy and Emissions Indicators (all data for 2009)

	Australia	Canada	USA	Finland	France	Germany	Sweden	UK
Electricity consumption per capita (kW-h/capita)	10,790	15,449	13,268	16,439	7,894	7,108	15,477	5,742
Change from 1990-2009	6%	-9%	-3%	8%	9%	7%	-1%	-6%
Oil self-sufficiency (production/consumption)	59%	178%	43%	1%	2%	3%	0%	100%
Change from 1990-2009	-40%	21%	4%	304%	-29%	0%	0%	-44%
Natural gas self-sufficiency	166%	171%	89%	0%	1%	12%	0%	61%
Change from 1990-2009	12%	-14%	9%	0%	-66%	-44%	0%	-46%
Total energy self-sufficiency	257%	155%	78%	48%	51%	39%	64%	73%
Change from 1990-2009	19%	5%	7%	2%	-2%	-3%	0	-40%
Renewables as per cent of electricity production	7%	62%	10%	30%	13%	16%	58%	7%
Change from 1990-2009	-2.4%	-0.2%	-1.2%	0.6%	-0.4%%	12.5%	7.4%	5.0%
Nuclear as per cent of electricity production	0%	15%	20%	33%	76%	23%	38%	19%
Change from 1990-2009	0%	-0.2%	0.8%	-2.7%	1.0%	-4.8%	-8.5%	-2.1%
Electricity as per cent of TFC	25%	24%	24%	29%	25%	21%	35%	22%
Change from 1990-2009	5%	1%	6%	6%	6%	5%	3%	5%
TFC (PJ, net of non-energy uses)	3,092	7,284	55,789	963	6,212	8,438	1,270	5,193
Change from 1990-2009	31%	10%	3%	3%	4%	-16%	-6%	-10%
Carbon intensity of electricity (g/kWh)	853	167	508	205	90	430	43	450
Change from 1990-2009	5%	-18%	-12%[9]	-10%	-17%	-22%	-10%	-33%

9 1990 data for USA was not listed in International Energy Agency, Energy Balances for OECD Countries. The next closest year that was included (1995) was used as the base year.

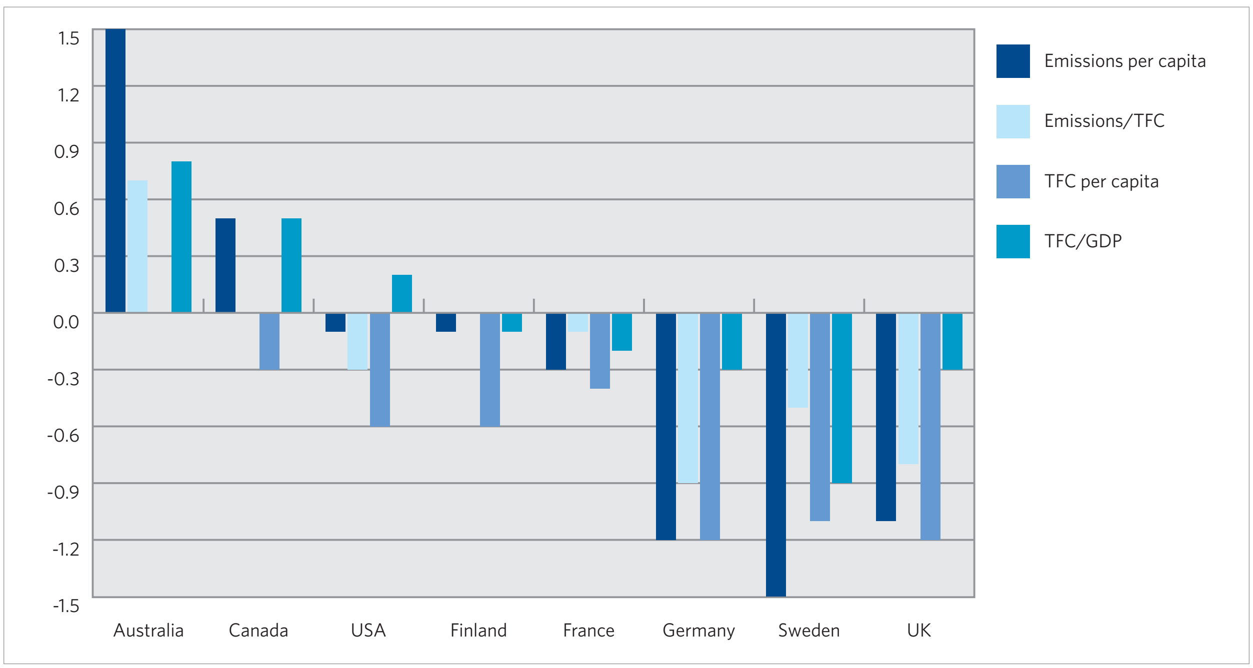
Table 3 and Table 4 reveal a range of current conditions with respect to the key indicators of greenhouse gas emissions. Canada, for example, shows relatively low emissions intensity in its final energy demand (lower than Germany or the UK), and also has the highest portion of renewable energy sources in its electricity supply (higher than Sweden). But these factors are overshadowed by the energy intensity of the Canadian economy and the relatively modest 24 per cent share of final energy demand supplied by electricity.

To a certain extent, Sweden's relatively low greenhouse gas emissions reflect the interaction of five interrelated factors that are increasingly seen as necessary in any low-carbon energy system:

- Highly efficient use of fuels and electricity
- Widespread use of combined heat and power (CHP) systems, and
- High levels of electrification of energy end uses (transport and heat), combined with
- Decarbonization of the electricity supply using renewables and/or nuclear, and
- Significantly increased reliance on biomass-based energy where electrification is not feasible.

As shown in Figure 2, the countries included in this review show a wide range of results for both energy intensity and emissions intensity. In the context of what an 80 per cent reduction in emissions might look like, it is interesting to note that the emissions intensities of the European nations, whether measured on a per capita or per GDP basis, are already 40 to 75 per cent below Canada's. And yet, as discussed below, the scenario analyses for those same European countries reveal the possibility of reducing those emissions by 80 per cent or more, implying emission intensities by 2050 that are 90 to 95 per cent below current Canadian levels.

Figure 2. Selected Country Indicators (Annual Growth Rates 1990-2009)



Summary Comparison of Low-Carbon Scenarios

The low-carbon scenarios in the eight reports we reviewed use different base years, and reflect different assumptions about underlying drivers such as population and economic growth. Their methods differ in detail and sophistication, but they all use the year 2050 as a focal point for scenarios in which energy-related greenhouse gas emissions are reduced to roughly 20 per cent or less of current levels. Table 5 summarizes the population and economic drivers for the scenarios we compared.

Table 5. Summary Comparison of Population and Economic Growth in Low-Carbon Scenarios Reviewed

	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
Base year	1999	2007	2000	2007	2000	2006	2005	2000
Population growth rate to 2050	**0.53%**	**0.68%**	**0.90%**	**0.17%**	**0.11%**	**-0.21%**	**0.35%**	**0.50%**
Population in 2050, millions	27	45	444	6	67	75	11	76
Per cent increase in population from 2009-2050	24%	32%	44%	7%	5%	-8%	15%	23%
GDP growth rate to 2050	2.3%	1.8%	2.4%	1.8%	1.7%	1.1%	2.3%	2.0%
GDP in 2050, billions of 2000 USD	**1,371**	**1,737**	**30,515**	**293**	**2,940**	**3,181**	**713**	**3,777**
Per cent increase in GDP from 2009-2050	156%	105%	169%	108%	100%	59%	149%	125%

In the assumptions about population growth, an historical difference between the European and United States/Canada/Australia (UCA) groups is projected into the future and amplified. Except for the UK (with a population growth forecast of 0.5 per cent per year), population growth in the European countries is 0.35 per cent per year or less, and Germany's is actually negative, averaging 0.21 per cent per year from 2006 to 2050. Projected population growth in the UCA group is much higher. Clearly, all else being equal, the higher population growth rates that underlie the American and Canadian scenarios will drive up emissions, particularly those related to household energy use, personal transportation, government, education, and health care.

All the studies project continuing growth in productivity and GDP. With the notable exception of Germany (for which GDP is projected to grow at 1.1 per cent per year over the long term), GDP growth rates are in the range of 2 per cent per year, implying a doubling or more of the real value of economic output by 2050. The relatively low population growth rates assumed in the European studies are largely offset by relatively high growth in labour productivity.

Table 6. Summary Comparison of Low-Carbon Scenarios in 2050

	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
Base year	1999	2007	2000	2007	2000	2006	2005	2000
Primary Energy Supply in 2050, PJ	**3,981**	**5,923**	**50,374**	**720**	**6,495**	**8,066**	**1,554**	**5,935**
Share of Primary Energy Supply in 2050								
Fossil fuels	46%	38%	40%	18%	42%	52%	24%	61%
Biomass[10]	33%	17%	34%	41%	18%	20%	38%	19%
Carbon-free electricity	**17%**	**45%**	**26%**	**41%**	**41%**	**19%**	**35%**	**20%**
Direct solar and geothermal heat	3%	0%	0%	0%	0%	9%	3%	0%
End Use Energy in 2050 (PJ)	3,533	4,280	49,306	659	5,792	5,845	1,340	4374

10 In this report, we use the term 'biomass' to refer to primary energy (analogous to crude oil), and calculate it as the heat of combustion. 'Bioenergy' refers to secondary or end uses, including liquid, gaseous, and solid fuels. 'Biofuels' refers to liquid fuels only, 'Biogas' refers to gaseous fuel, and 'Solid Biomass' refers to solid fuels.

	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
Share of End Use Energy in 2050								
Fossil fuels	28%	25%	35%	9%	19%	48%	23%	38%
Bioenergy	13%	12%	34%	48%	10%	17%[11]	27%	21%
Carbon-free electricity	56%	51%	24%	43%	72%	23%	47%	41%
Direct solar and geothermal heat	3%	12%	7%[12]	0%	0%	12%	3%	0%
Energy-related emissions in 2050, Mt CO2e	106	29	800	7.1	32	21	12	119
Carbon capture and storage?[13]	No	No	No	No	No	No	Yes	Yes
Nuclear power?	No	No	No[14]	Yes	Yes	No	Not specified	Yes

11 In the German report, about a third of the 17 per cent contribution from bioenergy is comprised of hydrogen from renewable electricity.

12 U.S. figure comprises 1 per cent direct renewables and 6 per cent hydrogen.

13 Many of the studies include multiple scenarios, but we have selected only one from each for our inter-country comparisons. Of the selected scenarios, only the UK incorporates CCS, but CCS does play a role in some of the alternative scenarios in the studies for Finland, France, Sweden and Germany. CCS was either disallowed, or considered but not included in any of the scenarios, for Canada, the United States, and Australia. Further discussion of CCS appears later in this report.

14 The table contents refer to the specific scenarios in each study that we used for inter-country comparison; the U.S. study did include nuclear in one of its other scenarios.

In the low-carbon scenarios, there are some significant shifts in the contributions to total primary energy supply.[15] Table 6 shows the fossil fuel share dropping to 50 per cent or less in most of the scenarios, with the exception of the UK, where large-scale deployment of carbon capture and storage (CCS) allows fossil fuel consumption to continue at higher levels through 2050. The shares of renewable and carbon-free electricity, and biomass for both solid and liquid fuel production, grow dramatically compared to current levels. Table 7 contains other selected indicators that illustrate some important features of the low-carbon scenarios we reviewed, and underscore the transformative nature of such futures.Per capita final consumption of energy declines in all the country scenarios, but the drop is more modest in the European countries, where base year per capita energy consumption is already significantly lower than in the UCA group. With the exception of the UK study, the scenarios rely almost exclusively on efficiency improvements to achieve lower per capita energy consumption, and the results indicate a convergence in the range of 100 GJ per capita.

- The UK study uses a constrained linear programming optimization model which incorporates estimates of energy service price elasticities. As a result, higher energy prices implied by the 80 per cent emission reduction constraint trigger reductions in the level of energy services provided, not just gains in the efficiency with which fuels and electricity were used. This is why per capita energy use, at 58 GJ per capita, is so much lower than in the other country scenarios.
- On a per GDP basis, the drop in energy intensity is much steeper, reflecting both efficiency improvements and a continuing decoupling of growth in GDP from growth in fuel and electricity consumption. (This phenomenon is explored in more detail in one of the companion papers to this report, Canadian Greenhouse Gas Emissions –Current Patterns and Historical Trends.) The carbon intensity of energy consumed also declines several-fold in all the low-carbon scenarios, reflecting strong growth in carbon-free electricity and the adoption of biomass fuels and other carbon-free sources of heat, fuel, and electricity. The net result is a very steep decline in both per capita greenhouse gas emissions and emissions per dollar of economic output. Energy-related greenhouse gas emissions drop to one tonne per capita or less, levels lower than have prevailed in the industrial economies in more than 100 years.
- Much higher levels of energy efficiency, greater electrification of end uses, decarbonization of the electricity supply, and increased use of biomass are key drivers in all the low-carbon scenarios. The trend to greater use of electricity for heat and mobility contributes to efficiency gains, since electrical technologies can achieve higher levels of end use efficiency than combustion technologies. At the same time, the options available for producing carbon-free electricity make it possible to complement the efficiency gains from electrification with much lower levels of carbon intensity.
- Still, there are limits to the current feasibility of using electricity in some end uses, and the most aggressive electrification in the low-carbon scenarios (France) achieves just 50 per cent electrification of final energy consumption by 2050. To reduce the carbon intensity of the remaining 50 per cent or more of energy end use, most of the scenarios turn to various strategies for employing biomass on a much larger scale than has been the case historically.

15 Primary energy is not defined in the same way in all the scenarios reviewed, with some setting the primary contribution from renewable electricity and nuclear at the high value (using the fossil fuel equivalence method or, in the case of nuclear, the estimated heat generated in the core) and others setting primary electricity at the lower, actual generation level. To facilitate the comparisons in this table, we have counted primary electricity for all the direct renewable sources (hydro, wind, solar photovoltaics, ocean) and for nuclear at the level of actual generation.

Table 7. Selected Indicators from Low-Carbon Scenarios[16]

	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)[17]	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
Per Capita End Use of Energy, GJ								
In 2009	140	216	181	180	96	103	137	84
In 2050	129	96	111	115	91	78	125	58
% Reduction	8%	56%	39%	36%	5%	24%	9%	31%
End Use Energy Per GDP, GJ								
In 2009	5.8	8.6	4.9	6.8	4.2	4.2	4.4	3.1
In 2050	3.9	0.7	1.8	1.2	0.5	0.3	1.1	1.6
Energy productivity improvement	33%	92%	63%	82%	88%	93%	75%	48%
Carbon Intensity of End Use of Energy, kg CO2e/GJ								
In 2009	127.7	71.5	93.1	57.1	57.0	88.9	32.8	89.7
In 2050	30	7	16	11	6	4	9	27
Reduction in carbon intensity of energy	77%	90%	83%	81%	89%	96%	73%	70%

16 To facilitate inter-country comparisons, the 2009 indicators are based on the International Energy Agency, *Energy Balance for OECD Countries* used for Table 2 and Table 3.

17 Some of the data from Lovins and Rocky Mountain Institute, *Reinventing Fire* was only available in graphical form, requiring that values be estimated from the graphical presentations.

	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)[17]	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
Emissions Intensity of GDP, kg CO2e Per Thousand USD								
In 2009	738	615	457	390	241	375	146	278
In 2050	77	17	26	24	11	7	17	32
Reduction emissions intensity of GDP	90%	97%	94%	94%	95%	98%	88%	88%
Per Capita Greenhouse Gas Emissions, Tonnes CO2e								
In 2009	17.9	15.4	16.9	10.3	5.5	9.2	4.5	7.5
In 2050	3.9	0.7	1.8	1.2	0.5	0.3	1.1	1.6
Reduction per capita GHG emissions	78%	95%	89%	88%	91%	97%	76%	79%
Per Cent of End Use Energy Provided by Electricity								
In 2009	24%	21%	21%	27%	23%	19%	33%	21%
In 2050	25%	45%	32%	43%	51%	27%	38%	41%
Per Cent of Energy Use Provided by Renewables								
In 2009	2%	13%	2%	8%	3%	3%	19%	1%
In 2050	48%	76%	62%	67%	49%	52%	93%	31%
Per Cent of Electricity System Powered by Fossil Fuels								
In 2009	93%	23%	70%	37%	11%	61%	4%	74%
In 2050	26%	5%	10%	0%	23%	18%	0%	26%

Low-Carbon Scenarios: Common Themes and Differences

Energy-related greenhouse gas emissions are the product of three factors:

1. The efficiency with which fuels and electricity are applied to energy service demands
2. The carbon intensity of the fuels and electricity, including their production and any application of carbon capture and storage
3. The level and pattern of energy services demand (heat, mobility, information processing, etc.) that drives the demand for fuels and electricity.

The development of any low-carbon scenario must necessarily be based on assumptions, whether implicit or explicit, in each of these areas. In the low-carbon scenarios we reviewed, most of the explicit analytical effort focuses on the first two categories of assumptions described above: energy efficiency and carbon intensity. The third category—the level and pattern of energy services demand—is usually determined implicitly in the development of the “business as usual” or “reference” projection of population and economic activity. Some of the scenarios (Finland, the UK, and the U.S.) do include explicit analysis of this third factor.

The scenarios reveal a number of common themes, as well as areas where particular national circumstances lead to unique approaches to carbon reduction. There is a high degree of interdependence between these factors, particularly between increased energy efficiency, greater electrification of energy end uses, and decarbonization of the electricity supply. For example, electrification of vehicles allows much greater energy efficiency at the point of end use, but it is the combined impact of greater end use efficiency and decarbonization of the electricity supply (whether through renewables, nuclear, or carbon capture and storage) that creates the possibility of very low-emission transportation. In addition, if the electricity is decarbonized using direct renewable sources like wind power, the shift in supply source leads to reductions in thermal power plant losses, one of the largest inefficiencies in the overall energy system. In general, low-carbon futures create a greater role for systems thinking and integrated design in which the benefits, including reductions in greenhouse gas emissions, are greater than the sum of the parts.

Energy Efficiency

Low-carbon futures are invariably futures with high levels of technological efficiency of fuel and electricity use. In all the scenarios we reviewed, energy efficiency gains were identified as necessary for the achievement of deep reductions in energy-related greenhouse gas emissions.

Efficiency improvements in fossil fuel combustion lead to direct reductions in greenhouse gas emissions, but efficiency’s most important role in a low-carbon future is actually indirect. A high level of end use efficiency is a necessary enabling condition for a variety of carbon-free sources of fuel and electricity to realize their potential contributions to a low-carbon future. The high per cent contributions to total energy end use from renewable electricity and various forms of biomass-based energy that we see in low-carbon futures (see Table 7) are only possible because efficiency gains have reduced the final demand for fuels and electricity to levels at which the feasible supply of carbon-free energy sources can provide a significant share.

The energy efficiency gains in the low-carbon scenarios occur across all sectors, and are significant relative to current practice. Even in the European countries, where the energy efficiency of buildings, technology, and infrastructure is already much greater than in the UCA group, the low-carbon scenarios include significant additional gains. As already noted, these efficiency gains are very often tied to electrification of end uses that have historically been met with fuel-powered end use technologies. The electric vehicle is the most notable example of this phenomenon, but the move from boilers to heat pumps to provide low-temperature heat is an important element in some low-carbon scenarios, such as Sweden’s.

- In the German scenarios, the specific heat intensity of residential and commercial buildings drops to 40 per cent of base year levels, and the specific fuel intensity of private cars drops by 42 per cent, freight transport by 35 per cent, and aviation by 32 per cent, with the average efficiency of the private car fleet in 2050 reaching 3.8 L/100 km.

- In the French scenarios, energy efficiency improvements reduce overall final consumption by nearly 50 per cent in 2050, from a "business as usual" level of 10,750 PJ to 5,800 PJ. The efficiency of the vehicle fleet triples, partly reflecting the advent of electric vehicles, with the average for personal vehicles reaching 3 L/100 km by 2050. The energy efficiency of the building stock improves by 40 per cent and the specific energy intensity of industry is reduced by 15 per cent.

- The overall drop in final consumption in the Finnish scenarios varies from 0 to 50 per cent, 25 per cent in the scenario included in our inter-country comparisons (Scenario B from FPMO 2009). Demand for heat in buildings drops by 50 per cent, appliance and electrical equipment efficiency improves by 60 per cent, fuel efficiency of combustion-powered cars increases by 50 per cent, and there is an average 20 per cent improvement in the specific energy of industrial production.

- The Swedish study assumes that the specific energy intensity of industry will decline at about the same rate as industrial output increases (3.45 per cent per year), so that by 2050 industrial energy demand is only about 15 per cent higher than its base year (2005) starting level. The thermal efficiency of the building stock improves by 30 per cent, and an additional drop in heating demand of about 10 per cent is assumed due to climate change itself (although this is partly offset by an increase in cooling demand). Appliance and lighting efficiency improves by 30 per cent. The transport portion of the Swedish scenario relies heavily on switching to electricity and/or biofuels. Vehicle efficiency gains are not explicitly identified in the report.

- In the UK scenarios, a great deal of efficiency improvement is embedded in the baseline. Final demand for energy in the reference scenario is only slightly higher than the base year (2000) value of 6,000 PJ, even though population grows 23 per cent and economic output more than doubles.

- In the scenario used in our inter-country comparisons, final demand for energy drops from its reference value of 6,450 PJ to 4,375 PJ, but this 33 per cent decline is not all due to technological efficiency improvements. In the UK method, the MARKAL model uses exogenously input price elasticities of energy service demand to estimate reductions in demand for the different scenarios. These elasticities are greater for some sectors (eg. residential energy use, and some industries like chemicals) than for others (eg. personal transportation), and in the 80 per cent reduction scenario used here for inter-country comparisons, price-driven demand reductions range from 5 per cent for personal car use to as much as 30 per cent for agriculture, the chemical industry, and gas-heated residences.

- We estimate that at least half of the 33 per cent drop in final demand in the LC-80 scenario is due to these demand effects. The 33 per cent drop is relative to a reference scenario which itself already reflects average energy efficiency improvements on the order of 30 to 35 per cent across all sectors.

- In the Canadian scenario included in our inter-country comparison, final energy demand is 55 per cent below the reference or "business as usual" case, due to energy efficiency improvements across all end uses and sectors. Final demand for heat drops by 40 per cent relative to the business-as-usual outlook, and specific energy use of industry drops by 70 per cent. Transport energy intensity drops by 55 per cent, and the share of electricity in meeting the final demand for transport grows from almost zero today to about 50 per cent by 2050.

- The Australian scenario is drawn from the oldest of the studies we reviewed, completed in 2002. Efficiency improvements reduce final demand for energy in the industrial sector by 45 per cent, and in the commercial buildings sector by 55 per cent (building design and envelope improvements; more efficient lighting, and heating, ventilating, and air conditioning systems and equipment). In the residential sector, building improvements make only a small contribution to efficiency gains, with most of the 30 per cent drop in energy intensity due to efficiency gains in lighting and other household appliances and equipment. Vehicle efficiency gains reduce specific energy consumption in the personal transportation sector by 68 per cent, with two-thirds of the improvement due to the widespread transition to electric hybrid technology. For freight transportation, vehicle efficiencies improve by 40 per cent.

- The United States scenario uses the U.S. EIA 2010 annual energy outlook, which already contains significant energy efficiency gains in its baseline. Counting both the gains in the EIA Annual Outlook and the additional assumptions in the U.S. low-carbon scenario, automobile efficiency increases by more than 50 per cent. Truck efficiency gains are somewhat less, at about 45 per cent, but operations, logistics, intermodal shifts, and double trailers boost total savings to 75 per cent over the "frozen efficiency" projection. Building energy use is cut by over 50 per cent through a combination of more efficient technologies, smart controls, and integrative design. The industrial sector scenario includes a 30 per cent efficiency improvement from energy efficiency and integrative industrial design.

The declines in per capita final energy consumption shown in Table 7 are mostly the result of these efficiency gains, and the attainment of low-carbon futures rests on the prospects for making these assumptions a reality. The per cent gains are themselves within the capabilities of existing technologies, and most of the studies argue that they are also cost-effective compared with fuel and electricity prices, especially with the prices that would prevail in a carbon-constrained system. However, achieving per capita fuel and electricity consumption levels in the range of 100 GJ in Canada will require a widespread technological transformation in the efficiency of fuel and electricity use. In most instances, deployment is clearly much more of a challenge than technological feasibility or even fundamental economic feasibility, suggesting that the greatest need for innovation is in logistics, financing, and effective business strategies.

Figure 3. Per Capita Energy Consumption (2009 vs. Scenario)

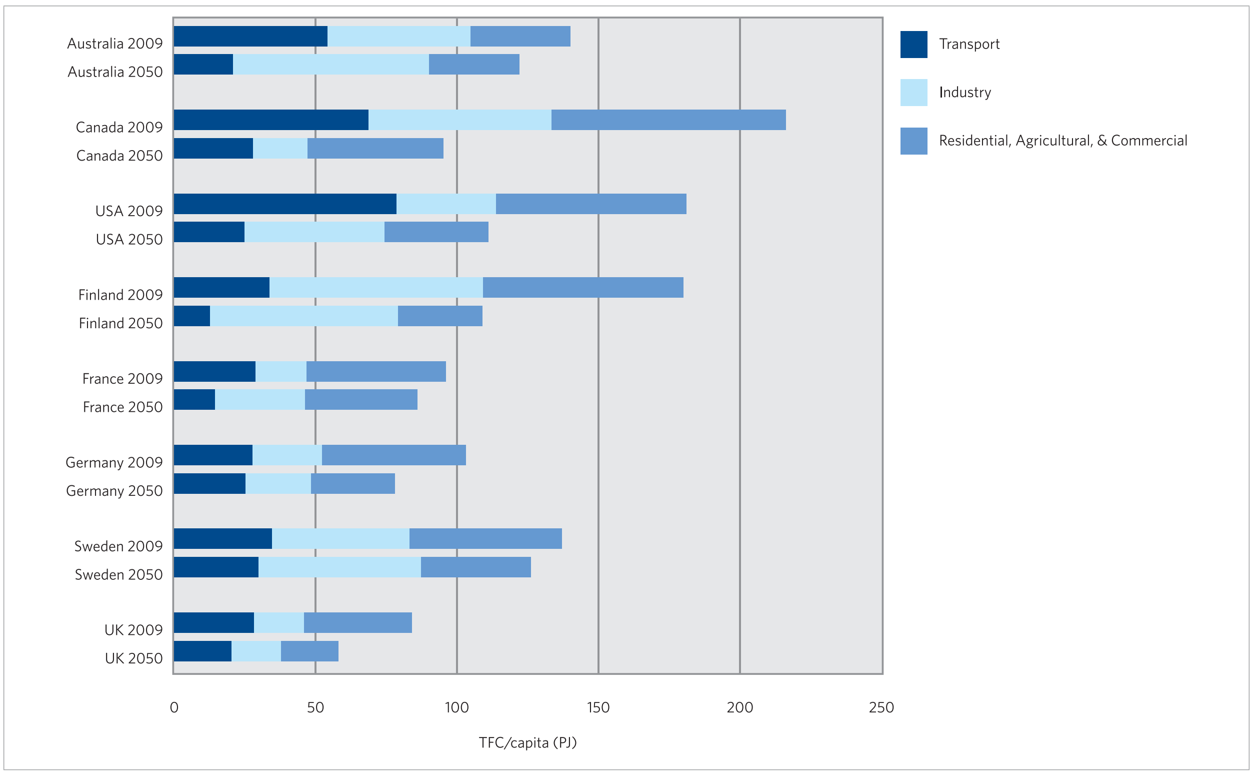
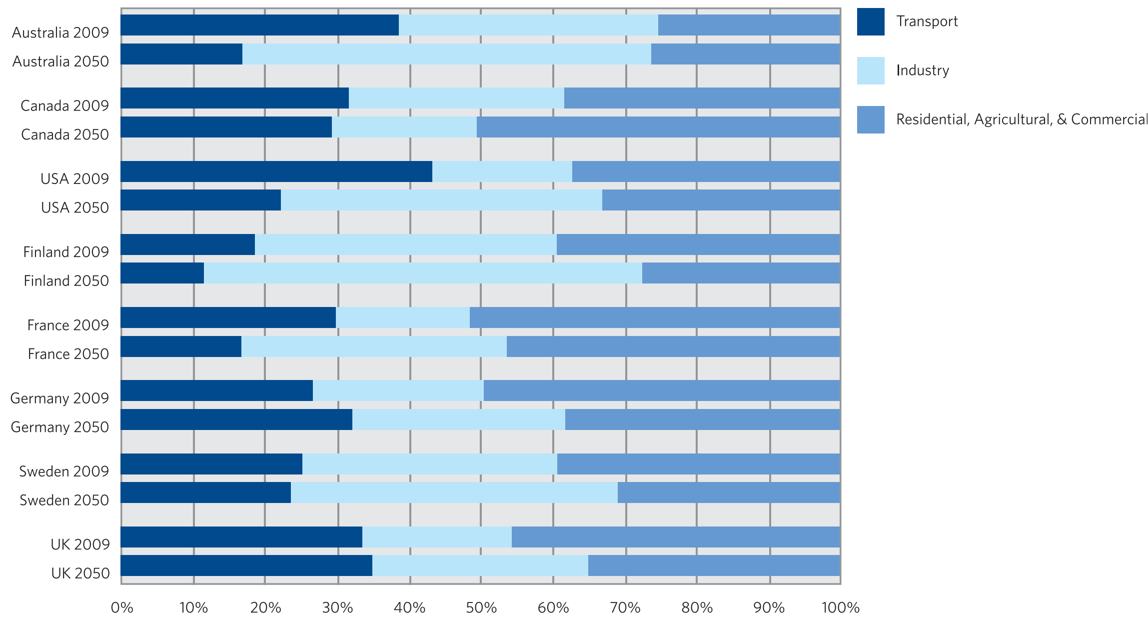


Figure 4. Share of Energy Demand by Sector (2009 vs. Scenario)



Renewable Electricity

Along with the large gains in efficiency of fuel and electricity end use described above, strong growth in various forms of renewable electricity generation is a universal feature of all the scenarios. The combination of increased electrification of energy end uses with the simultaneous decarbonization of the electricity supply is one of the defining features of low-carbon energy futures, and the renewable electricity technologies play a central role in that decarbonization.[18]

Carbon-free, renewable electricity can be generated from hydroelectric, wind, geothermal, photovoltaic, biomass, wave, or tidal energy. Of this group, hydro and wind power are generally regarded as having the largest potential, but the U.S. study in particular shows very significant contributions from both solar photovoltaic and concentrated solar power plants. (The Trottier Energy Futures Project's assessment for Canada appears in a companion paper to this report, *An Inventory of Low-Carbon Energy for Canada*.)

Table 8 profiles the electricity supply from the scenarios included in our inter-country comparison. In all the low-carbon scenarios, carbon-free power provides most of the electricity by 2050, ranging from 74 per cent in the UK (where carbon capture and storage is applied to further reduce emissions) to 100 per cent in Sweden and Finland. With the exception of the CCS-equipped facilities in the UK scenario, large thermal power plants are all but phased out in these scenarios, although several of the scenarios include continued use of small to medium-sized gas-powered combined heat and power plants.

18 Nuclear power and carbon capture and storage (CCS), discussed below, are two other options for decarbonizing electricity.

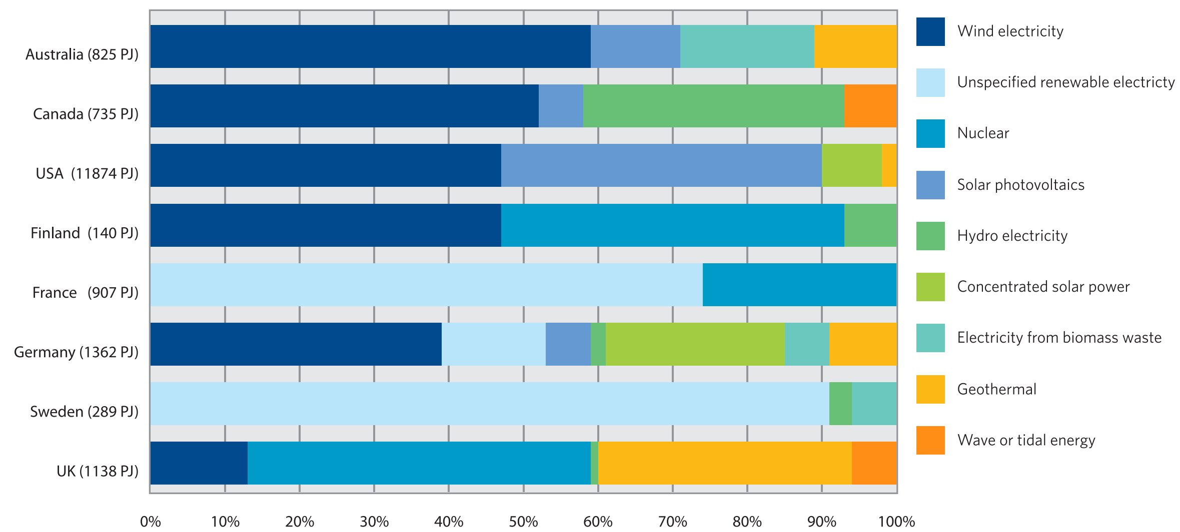
Table 8. Renewable Electricity Supply in the 2050 in Low-Carbon Scenarios (PJ)

Petajoules	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
Hydro electricity	0	1,572	995	55	Not specified	89	245	31
Wind electricity	500	396	5,897	67	Not specified	672	Not specified	188
Solar photovoltaics	100	43	5,163	0	Not specified	100	Not specified	0
Concentrated solar power	0	0	920	0	Not specified	327	Not specified	0
Electricity from biomass	157	7	192	14	Not specified	194	59	38
Geothermal	91	0	228	0	Not specified	128	Not specified	387
Wave or tidal energy[19]	0	50	0	0	Not specified	Not specified	Not specified	64
Unspecified renewable electricity	0	0	0	0	924	190	0-263[20]	0
Nuclear	0	0	0	150	1710	0	0-263	769
Total carbon-free electricity	847	2,041	13,395	286	2,634	1,699	566	1,477
Carbon-free as per cent of electricity supply	74%	95%	90%	100%	77%	82%	100%	74%

19 Tidal in the case of Canada, wave in the case of the UK.

20 The Swedish study did not specify the supply shares for renewables and nuclear, but lumped them all together in a single carbon-free supply total, noting that the 263 PJ could be all nuclear, all renewable, or some combination.

Figure 5. Composition of Carbon-Free Electricity Increase (2009-2050) in Low-Carbon Scenarios



While significant reliance on carbon-free, renewable electricity is a common feature across all the scenarios, the studies reflect differences in the contribution of the various supply sources in specific countries.

- Despite large potential for future development, hydropower is not a significant contributor to growth in carbon-free electricity except in Canada and, to a lesser extent, Finland.
- In general, wind power is the dominant source of renewable electricity growth, with photovoltaics and other renewable electricity technologies playing secondary roles. The German and U.S. studies are exception insofar as they 'envision a relatively large role for solar electricity, mostly from photovoltaics.
- With the exception of Germany, the European studies include at least some scenarios that anticipate a role for nuclear. Wind accounts for the largest percentage of growth in scenarios that exclude nuclear.
- The scenarios play to regional strengths, with desert areas contributing more than 40 per cent of the new carbon-free electricity in the United States and geothermal accounting for more than 30 per cent in the UK.

The diversity of carbon-free electricity growth scenarios highlights the importance of considering all generation options in the Trottier Energy Futures Project scenarios.

Nuclear Power

Nuclear power is included in three of the scenarios selected for the inter-country comparisons (France, Sweden and the UK, see Table 8), the U.S. study includes scenario variations with a continued role for nuclear, and Sweden combines renewables and nuclear in a single total for carbon-free supply. Generally, those studies that address nuclear generation delineate a choice between reliance on nuclear and a shift towards energy efficiency and renewable energy, with some authors expressing a clear preference for efficiency and renewables.

The Canadian study, for example, dedicates a chapter to nuclear power and provides a rationale for excluding it as a low-carbon option. The German scenario includes a phase-out of nuclear power by 2030, with the authors commenting that extending the phase-out deadline would "fundamentally call into question the requisite structural change of power supply" towards greater efficiency, renewables, and cogeneration. Although Australia is a major global supplier of uranium, the country has not developed any domestic nuclear capacity, and the option was not considered in the Australian scenario analysis.

- In the studies that include nuclear power in at least one of their scenarios (U.S., UK, France, Finland, Sweden), the option is generally presented as an alternative to the high rates of efficiency improvement and renewable electricity development that are otherwise required to decarbonize the electricity supply. The French study, for example, projects end use efficiencies of 75 per cent for a non-nuclear scenario with cogeneration, 60 per cent with nuclear generation, and 48 per cent with greater reliance on nuclear-based hydrogen.
- As noted above, the Swedish study does not specify the contribution from nuclear power in a low-carbon future. The country's base year (2005) nuclear power production was 252 PJ. The 2050 scenario calls for 270 PJ total production of nuclear and renewable electricity, without identifying the mix.
- With significant carbon reductions as a common assumption, the Finnish scenarios largely present a trade-off between changes in lifestyle and consumption patterns and reliance on nuclear electricity. Nuclear is phased out in a scenario where efficiency doubles, passenger transportation declines, urban structures are more tightly interconnected, and the service economy grows at the expense of traditional industrial production in primary metals and paper. Nuclear power is expected to triple in the absence of these demand reduction factors. In the scenario used for the inter-country comparison in this review, Finnish nuclear power doubles from its current levels and provides 40 per cent of the electricity supply in 2050. The Finnish scenario also includes 39.2 PJ of nuclear plant condenser heat for district heating.
- The U.S. study includes four scenarios for the future electricity system in which nuclear's contribution varies from zero to 36 per cent of total electricity supply in 2050. In the high nuclear scenario, called "Migrate", the renewable share drops to 17 per cent of total generation. In the "Transform" scenario used for the inter-country comparison in this review, nuclear is phased out and renewables provide 90 per cent of the electricity supply. In the "Renew" scenario, in which renewables meet 81 per cent of U.S. electricity demand by 2050, the 9 per cent contribution from nuclear requires output close to current levels.
- The UK LC-80 scenario used in the inter-country comparisons includes 764 PJ of nuclear electricity in 2050, 2.5 times the country's nuclear generation in 2010. This is the highest growth rate for nuclear in any of the scenarios. However, the UKERC exercise generated 32 separate scenarios, and the variation in the nuclear contribution is instructive. For instance, if the availability of low-cost renewable energy is accelerated, the contribution from wind power increases four-fold from its LC-80 value, while nuclear drops back to 279 PJ, a little lower than current nuclear output.

The UK study also simulates a complete phase-out of nuclear generation, resulting in even higher growth of wind power, to 1,300 PJ by 2050, compared with 188 PJ in the basic LC-80 scenario. In yet another variation, entitled ECO, limits are placed on the development of several technologies that are seen to impinge on ecosystem services—onshore wind, offshore wind, tidal power, biomass imports—resulting in nuclear output of 1,100 PJ in 2050, three times the output of the UK's current nuclear program, and nearly 50 per cent higher than the nuclear output in the basic LC-80 scenario.

Another interesting variation, based on a 60 per cent GHG reduction by 2050, begins with 375 PJ from nuclear, then assumes moderately lower costs, higher load factors, and availability of Generation III technology by 2017 for a first-of-a-kind plant. The result is a 40 per cent increase in the contribution from nuclear power by 2050. In general, however, the potential for advanced generations of nuclear technology was not explicitly covered by the studies reviewed.

Carbon Capture and Storage

Carbon capture and storage (CCS) technology is considered in all the studies we reviewed, and is included in several of the scenario variations. In general, uncertainties over cost and performance result in CCS being treated as a contingency against the possibility that fossil fuel combustion cannot be phased out through energy efficiency measures and carbon-free alternatives. CCS is omitted altogether in the Canadian and Australian scenarios.

CCS is a capital-intensive technology that as currently envisaged would be most cost-effectively applied in large-scale applications such as power stations and primary industrial plants (cement, paper, chemicals). It is also unlikely to proceed without a strong policy impetus for carbon reduction. It is most likely to be deployed in jurisdictions where fossil fuels, and especially coal, have a central role in the electricity sector, such as the UK. In jurisdictions where it is possible to phase out dependence on fossil fuel power sooner rather than later, through deployment of nuclear and/or renewable electricity, CCS may not be needed to meet a low-carbon target.

- In the UK, CCS is the primary method of electricity decarbonization in the early years of the scenario period. In the LC-80 scenario used for the inter-country comparisons, CCS technology comes onstream by 2020, reaches 800 PJ of coal-CCS production by 2030, and maintains that level through the scenario period. The UK research concludes that the optimal mix of wind, nuclear, and CCS in meeting carbon targets is difficult to determine, given the overlapping and uncertain future cost estimates for the three technologies. Also, for very deep carbon reduction objectives, the residual emissions from CCS plants become problematic over the long term, creating an advantage for the nuclear and renewable supply options.
- In the Swedish scenario, CCS contributes 5 Mt CO2e per year to carbon reductions by 2050. Energy-related emissions drop to 17 Mt CO2e in 2050 without CCS. With CCS added, emissions reach 12 Mt CO2e, 79 per cent below the base year level. The Swedish study includes another interesting application of CCS: capturing biogenic carbon from pulp and paper mills to offset the continued use of fossil fuels in the transport sector, thereby allowing a “go-slow” approach to the introduction of biofuels in the transportation sector.
- Several studies highlight CCS as a research priority. The French study, for example, concludes that either nuclear power or CCS will be needed to account for variability and intermittence in distributed renewable energy supplies, and determines that CCS adds resilience to the low-carbon scenarios for transportation (by permitting extended use of fossil fuels) and heavy industry.
- The German study includes up to 18 GW of CCS capacity by 2050 as a mitigating factor in a scenario that allows more coal-fired power production. (Further CCS applications would be required in the supply of heat and fuels.) However, the study concludes that a combination of efficiency and renewables would be the lowest-cost emission reduction option.

Biomass

While increased electrification of energy end uses combined with decarbonization of electricity is a key strategy in all the scenarios we reviewed, the highest share of electricity as a per cent of total energy use is in the French scenario, at 51 per cent (see Table 7). For the rest of the energy end use pie, various forms of bioenergy are considered essential to achieving low-emission outcomes, and in the low-carbon scenarios included in our inter-country comparison, biomass provides 17 to 41 per cent of primary energy (see Table 9).

But despite its prominence in most low-carbon scenarios, recent experience with bioenergy has made its use somewhat controversial and problematic. Key issues include the longstanding trade-off between food and fuel crops, especially in the area of biofuel production, which to date has relied primarily on corn-based ethanol. There are also technical limitations on the ability to produce sufficient quantities of bioenergy at a realistic cost, and without impacts on biodiversity.

Of all the low-carbon studies, Canada’s Energy [R]evolution goes into the greatest detail in establishing a sustainability lens for future bioenergy development, using criteria developed for Greenpeace International by the German Biomass Research Centre. The criteria stipulate that bioenergy projects:

- Have a positive GHG balance of at least 60 per cent over their full life cycle, which favours more efficient applications such as electricity and heat production over transport
- Must not cause direct or indirect destruction or conversion of natural forests or other natural ecosystems
- Use biomass in an environmentally responsible and socially just manner, as measured by certifications like the Forest Stewardship Council (FSC)
- Proceed in a way that avoids social conflicts and protects food security, livelihoods, and indigenous land rights
- Involve no deliberate release of genetically engineered organisms to the environment
- Promote biodiversity by minimizing monoculture plant and tree plantations
- Apply sustainable agricultural practices that do not pollute the biosphere through accumulation of agrochemicals like synthetic fertilizer, pesticides, and herbicides in the soil, water, or air
- Conserve water and promote soil fertility
- Should not introduce any invasive species

Table 9. Treatment of Biomass in 2050 Scenarios

	AUSI 2002 (Australia)	EREC 2010 (Canada)	RMI 2011 (USA)	PMO 2009 (Finland)	MIES 2004 (France)	BMU 2008 (Germany)	IVL 2010 (Sweden)	EKERC 2009 (UK)
2050 biomass use	1331 PJ (33% of primary energy supply)	994 PJ (17% primary energy demand)	17,228 PJ (34% primary energy consumed)	319 PJ (41% final energy consumed)	Unspecified	1615 PJ (20% of primary energy supply)	359 PJ (26.8% end use demand)	910 PJ (20.8 % final energy demand)
Sectors consuming biomass/end-uses	Transportation, electricity, heat, industry, commercial, residential	Heating, electricity, transportation	Transportation, electricity, industry	Heating, electricity	Unspecified	Heating, electricity	Transportation	Transportation, service, electricity
Feedstocks	Unspecified crops, forestry plantations, crop and food industry wastes	Crop harvest and process residues, wood processing residues, bioenergy crops		Wood processing residues, wood chips	Not specified	Residual wood, biogenic wastes, fuel crops	Round wood, forest residue, energy crops, agricultural and household waste	Wood, ligno-cellulosic crops, bio pellets, bio-oils, biodiesel, ethanol, methanol, biogases, bio-methane and wastes
Amount of feedstock/Biomass imported	None	None	None	Not specified	Not specified	20%	None	33%
Discuss sustainability framework to produce?	No	Yes	No	No	No	Yes	No	No

Despite these restrictions, Energy [R]evolution projects that biofuels demand will increase from 28 to between 75 and 235 PJ per year[21], depending on the scenario.

21 This is 235 PJ of secondary or end-use energy and, as such, it does not include the losses incurred in the conversion from biomass to biofuel.

The German study also applies restrictions to biofuel production, including a cap on land cultivated for biofuels (2.35 million hectares) and a requirement that no food crops be displaced. As in Canada, biofuel production is nonetheless expected to grow substantially, in this case six-fold between 2005 and 2050.

The Swedish study reviews the technical energy potential of forestry biofuels based on extraction projections under various market and environmental constraints. It concludes that between 90 and 648 PJ of primary wood feedstock will be available for biofuels. The report explicitly rules out any biomass imports for fuel production. Production shifts from ethanol to a mix of syngas (25 per cent of total production), biogas (25 per cent), and dimethyl ether (50 per cent) to capture conversion efficiencies greater than 65 per cent, compared to 32 per cent for ethanol. No other study imposes sustainability criteria on biofuel development, and all project significant growth in biofuel production and demand.

The Australian study appears to pursue biomass and biofuel production most aggressively. Australia's biofuels scenario includes contributions from plantation forests, agricultural wastes, and about six to seven million hectares of dedicated farmland. The government is currently attempting to increase plantation lands to three million hectares by 2020, en route to eight million by 2050. The requirement for biofuels doubles when the scenario target increases from a 60 per cent GHG reduction to 70 per cent, reflecting the intense marginal pressure that would be exerted on biomass resources in a low-carbon scenario.

In the UK LC-80 scenario, the end use of bioenergy grows from a current level of 25 PJ from all sources to 393 PJ of ethanol, 338 PJ of biodiesel, and 176 PJ of biomass fuel. Similar high growth rates characterize the U.S. scenario, in which bioenergy quadruples by 2050.

Hydrogen

Like electricity, hydrogen is an energy currency that emits no persistent greenhouse gas emissions at the point of end use, and can be produced from a variety of primary energy sources. Natural gas reforming is the predominant method for making the relatively small quantities of hydrogen used by industry today, but electrolysis of water is often the method presumed in energy scenarios that envisage a major role for hydrogen.[22] If this electrolysis is driven by renewable or nuclear electricity, the supply of hydrogen can be made carbon-free. The hydrogen can then be used as a direct combustion fuel, or to power fuel cells that produce heat and electricity.

There is still considerable uncertainty surrounding the technologies and infrastructure (both technological and institutional) that would characterize an energy future in which hydrogen plays a major role. Electrification of end uses, decarbonization of electricity, and the development of biomass-based liquid and gaseous fuels crowd out hydrogen in the near to medium term in the scenarios we reviewed, but it does start to play a significant role in some of the studies in the latter part of the scenario period.

Additional research and innovation will be needed to bring down the cost of the hydrogen option relative to biofuels and electricity. At the same time, there is concern about the ecological implications and the overall sustainability of the volumes of bioenergy required to meet the needs of the non-electric portion of the energy end use pie.

Across the eight low-carbon studies we reviewed, hydrogen was not included in the Finnish or Swedish scenarios, and has a very small role (less than 1 per cent of total energy use in 2050) in the Canadian scenario. After 2040, hydrogen begins to grow in the U.S. scenario, and supplies about 25 per cent of the transportation sector's end use energy by 2050, equivalent to about 7 per cent of total end use.

In the UK scenario, the high cost of hydrogen excludes it until the last few years of the scenario period. In 2050, it supplies 138 PJ, just 3 per cent of total end use energy. The optimization model used in the UK exercise allowed a number of scenario variants to explore how hydrogen deployment might be accelerated. When the scenario is run with a social discount rate governing the investment decisions, hydrogen begins to make a significant contribution in the 2030s (rather than the late 2040s), and by 2050 it has supplanted biofuels in the transportation sector.

22 Other hydrogen production methods are under development, including thermochemical methods that run at relatively low temperatures and with much smaller quantities of electricity than required for electrolytic production.

Three of the five low-carbon scenarios in the French study, including the one we used in this review, foresee a role for hydrogen from electrolysis. The three scenarios in which hydrogen is developed are also the three with the highest proportions of carbon-free electricity (nuclear and renewables). In the F4-RCogN scenario, hydrogen is used as an industrial fuel, and production in 2050 totals about 600 PJ, about 10 per cent of final energy consumption. In the F4 Hydrogen scenario variant, nuclear power increases to 7,000 PJ, 1.7 times current output, and hydrogen production of 1,200 PJ is used both as an industrial fuel and in the transport sector, where by 2050 it provides 20 to 25 per cent of end use energy.

In the German scenario, hydrogen produced from renewable electricity begins to come onstream after 2030. By 2050, it provides 183 PJ of end use energy, about 10 per cent of transportation sector requirements. A scenario variant (E3) includes earlier and faster deployment of hydrogen, all from renewable electricity, so that it contributes 20 per cent of transportation energy needs by 2050.

The German study also considers the prospects for a more significant role for hydrogen as an energy currency in the post-2050 period, when an excess of renewable electricity supply will be available for large-scale electrolytic hydrogen production. In this long-term view, the production of biofuels stabilizes at about its 2050 level of 320 PJ, and hydrogen becomes the energy currency of choice for further increasing Germany's reliance on renewable energy sources. Over the very long term, the German scenario envisages a completely renewable energy system by 2090, in which hydrogen provides 75 to 80 per cent of transportation energy and 25 per cent of total energy end use, and fossil fuels are used only for high value-added, non-energy applications. These very long-range projections assume significant development in enabling systems: The French study acknowledged that a shift to hydrogen would involve significant technical progress, major investment in costly hydrogen transportation infrastructure, and higher vehicle costs.

The Fossil Fuel Industry

Of all the countries included in this review, Canada is the only net exporter of petroleum. The European countries import their crude oil supplies, and neither Australia nor the United States is self-sufficient in petroleum resources. In these countries, a transition away from the domestic use of fossil fuels results in a decline in whatever petroleum refining industry exists, or a transition from petroleum to bioenergy refineries.

In Canada, however, even if domestic demand for fossil fuels (outside the fossil fuel industry itself) were reduced to zero, there would still remain the question of how much petroleum the country would produce for world markets, and with what carbon intensity. The Trottier Energy Futures Project is pursuing the realistic potential to decarbonize fossil fuel production as part of the development of a Canadian low-carbon scenario.

Energy Services Demand

The production and consumption of fuels and energy carriers such as electricity and hydrogen are driven by underlying demands for energy services: heat at various temperatures, personal mobility, goods movement, stationary motive power, light, information processing, and a variety of "electricity-specific"[23] end use services. These energy service demands are themselves derived from even more fundamental demands for comfort, good health, security, and happiness, and for access to related goods and services, education, employment, recreation, and cultural experiences.

The prevailing practice in energy policy and market analysis is to draw the system boundary around the fuel and electricity markets. Exogenous population and economic growth assumptions are used to drive growth in demand for fuels and electricity, usually with the implicit assumption that the future will look very much like the recent past with respect to the relationships between population and economic growth and the level and pattern of energy services demand. Factors such as the housing mix, personal mobility, technology choices, and even the mix of goods and services being produced are generally held at their current average or marginal values, or perhaps projected to change according to historical trends.

23 The term "electricity-specific" refers to energy end uses, which can only be provided by electricity. In practical terms, this includes lighting, small motors and appliances, telecommunications, information processing, and various industrial processes that are "necessarily electric" (eg. electrolysis). These end uses make up a relatively small portion of total energy end use in industrial societies, where heat and motive power typically account for 80 to 90 per cent of all energy end use.

A retrospective analysis of fuel and electricity demand patterns often reveals that changes in the underlying dynamics of energy services demand are more important in determining the level and pattern of fuel and electricity demand than changes in either technological efficiency or the fuel mix. In recent decades, the economic structures of all the OECD economies have trended toward greater economic output per unit of fuel and electricity consumed, reinforcing the simultaneous increase in the technological efficiency of fuel and electricity use.[24]

And yet, in most of the low-carbon scenarios we reviewed, there is only minimal exploration of this category of underlying factors. This may be because predicting changes in personal behaviour and societal shifts in values is even more tenuous than specifying the future development and deployment of low-carbon fuel and electricity technologies. Yet this additional layer of analysis is essential to capture the full potential, and map the most promising pathways, in the search for low-carbon energy futures.

The UK analysis includes an innovative approach to capturing at least some of the implications of changes in these underlying drivers by introducing fuel price elasticities of energy services demand. In the optimization model used for the UK study, increases in fuel and electricity prices trigger reductions in underlying demand for heat, mobility, and other energy services. As noted above in the discussion on energy efficiency, a significant part of the decline in per capita final consumption of fuels and electricity in the UK LC-80 scenario is due to the reduction in energy services demand triggered by these assumed elasticities.

This is an interesting and useful innovation as far as it goes, but the level and pattern of energy services demand across an economy result from a complex, dynamic web of factors, of which the price of fuels and electricity is only one component. It is sometimes a relatively important factor but, more often, prices play only a minor role in determining the demand for energy services. The optimization model used in the UK study only allows for a decrease in energy services to be represented as a loss in welfare, but reality is not so simple. The Internet, for example, has triggered immeasurable reductions in the demand for mobility, by curtailing demand for everything from personal shopping trips to face-to-face meetings and events. More broadly, information technology has led to dematerialization and the widespread displacement of fuel and electricity by information and design. Most would agree these developments have increased social welfare, and the long-term increase in the fuel and electricity productivity of the OECD economies reinforces the conclusion that economic development does not require and does not necessarily lead to increased fuel and electricity consumption.

Several of the low-carbon scenarios we reviewed include some “what if” analysis of how greenhouse gas emissions could be affected by changes in the level and pattern of energy services demand that are themselves the result of changes in economic activity that are not much influenced by energy market factors (eg. the Internet is not an energy efficiency measure, but it is having a profound impact on the demand for mobility and other energy services). Factors such as economic structure, dwelling type and size, and changes in personal mobility demand are varied in a number of the studies.

The Finnish study includes four scenarios that are specifically designed to draw attention to economic structure, urban form, personal values, and lifestyles, and a number of the other country scenarios include analysis of how changing levels and patterns of personal mobility could affect future transportation energy requirements. The U.S. low-carbon scenario, for example, estimates that “smart growth” measures (pedestrian- and transit-friendly urban development) would reduce total automobile passenger miles by 20 per cent by 2050 compared to “business as usual”. A number of the studies also point to the need to identify synergies between the objective of a sustainable, low-carbon energy sub-system and the trends and objectives that shape the behaviours and decisions that determine the level of energy services demand, even though those behaviours and decisions are not themselves much influenced by the dynamics of energy markets or energy policies.

24 International Energy Agency, Energy Balance of OECD Countries.

Cost and Economic Analysis

The low-carbon futures we reviewed vary in the extent to which they assess the costs of making the transition; Table 10 summarizes the different approaches taken. In general, these analyses share two conclusions, with varying degrees of substantiation, with respect to the cost and economic impacts of a transition to a low-carbon future.

- The cost of the energy system as a whole will increase in most scenarios, but it will be a modest increase compared to the overall cost of producing and supplying energy.
- Higher fuel and electricity prices will be moderated by increased energy efficiency, so that the overall economic impact of the transition will be relatively small compared to the size of the economy.

Some additional observations:

- We have already observed that to achieve their transformative targets, the studies rely primarily on increased efficiency of fuel and electricity use, greater electrification of end-uses such as heat and transportation, increased reliance on renewable and/or nuclear generation, and development of biomass-based fuel supplies. These options are characterized by relatively high initial investments, followed by very low annual operating costs. (Biomass-based fuels are an exception, due to the significant ongoing cost of growing primary biomass.) Energy efficiency investments epitomize this capital intensity, but renewable generation such as solar and wind power are also heavily dominated by the initial capital cost. The cost of low-carbon futures is therefore sensitive to the cost of capital and the assumed lifetime of the investments, as well as the capital costs of actual energy efficiency and renewable energy technologies that have been declining rapidly in recent years.
- In the case of electricity, the cost effectiveness and roles of individual technologies can only be determined in the context of a full systems analysis that takes into account the dynamics of the new grid, with all the interacting demand patterns, smart technologies, storage options, responsive loads, transmission and distribution alternatives, conventional generation options, reserve and backup requirements, and inter-grid transfers (i.e. enhanced east-west connectivity). There are tradeoffs, for example, between siting wind generation in locations where it can achieve higher capacity factors but is remote from markets, thereby necessitating more transmission investment. The carbon-free and low-carbon generation options that can help reach our 80% GHG reduction target will require that backup capacity be built and available to ensure continuous and reliable electricity supply. In general, the electricity system becomes more capital intensive in the transition to a low-carbon future, both because the costs of the renewable, efficiency and other technologies that are key to reducing carbon are dominated by capital costs, and because the intermittency of some of the new sources (especially wind and solar) require capital investments in the generation and storage necessary to maintain system reliability. The energy efficiency gains in low-carbon futures reduce expenditures on fuel and electricity compared to "business-as-usual." To a first approximation, the net, direct cost of the efficiency investments is the difference between the investment and the present value of the resulting savings. To the extent that these savings exceed the levelized capital costs of the efficiency gains, they represent an indirect and positive economic impact for the efficiency improvements.[25] It is generally agreed that there is significant potential to improve the efficiency of fuel and electricity use at low or even negative net cost[26], and this is a major factor in assessing the net economic costs of the transition to low-carbon futures. Fuel and electricity prices may increase, but the total cost of energy services (heat, mobility, light, information processing) will be moderated by the efficiency gains.

25 The respending of savings from efficiency measures will itself trigger additional fuel and electricity consumption—a form of the so-called "rebound effect". In the rich, industrial countries considered in this review, the rebound effect is secondary, and has been included only implicitly in most of the scenario analyses. (The fuel and electricity consumption associated with marginal income is relatively small throughout the OECD, where fuel and electricity consumed per dollar of GDP has been declining for decades).

26 See for example, Hannah Choi Granade, et. al., Unlocking Efficiency in the U.S. Economy (McKinsey & Company, July 2009).

- The future cost of fossil fuels is a factor in determining the cost and cost-effectiveness of low-carbon technology investments, and a key uncertainty in assessing the incremental economic impact of a low-carbon transition. As the cost of conventional energy resources rises and the cost of efficiency and low-carbon resources declines, the economics of the broader transition improve.
- Low-carbon scenarios typically assume that the future economy will have a structure very similar to the present one. Of course, the energy sector itself is an exception, but notwithstanding their importance to industrial economies, fuel and electricity markets constitute only a few per cent of GDP in most industrial countries. In Canada, for example, where well over half of oil and gas production is exported, constituting about a third of all the economic activity in the fuel and electricity industries, the energy sector contributes less than 7 per cent to the country's $1.7 trillion GDP.[27] The economy-wide impacts of changes in the energy economy must be viewed in this larger context.
- Another implication of the subsidiary role of the energy sub-system is the profound impacts that changes in the wider economy can have on the level and pattern of energy service demands. The economy that generates energy services demand is about 20 times larger than the energy industry that provides the fuel and electricity, and trends and events in that larger economy that are not much influenced by fuel and electricity markets (eg. the invention of the Internet, an aging population, changing housing preferences) will continue to have profound implications for both the prospect and the economics of a low-carbon future.

Table 10. Cost and Economic Analysis in the Reviewed Scenarios

Country	Summary of Cost Treatment
Australia	The study starts with a projection of the future Australian economy, then applies efficiency and low-carbon supply technologies that have lower unit energy costs than the retail prices for fuel and electricity that prevailed in western Europe in 2000. In the resulting scenario, energy efficiency improvements offset increases in fuel and electricity prices, so that households and industry pay less for energy in 2050 than they do today. This relatively simple method was characteristic of the first generation of low-carbon scenario analysis, and raised the possibility that a transition to a low-carbon energy system might be possible with relatively modest change in total cost of service provided.
Canada	The report states that the low-carbon Energy [R]evolution scenario would cost C$343 billion, compared to C$317 billion for the reference case. Electricity costs will initially increase with the investment in the low-carbon scenario, then decline after 2030, as the expansion of renewables stabilizes the system. The reference scenario indicates continuing increases in the cost of electricity supply due to an unchecked rise in demand, increased fossil fuel costs, and a future price on carbon emissions.
USA	Using the U.S. DOE Annual Energy Outlook as a point of departure, the RMI analysis calculates the net present value of the investments and savings required through 2050 to build the "Reinventing Fire" scenario. An investment of $4.5 trillion (NPV) yields savings of $9.5 trillion (NPV), for net savings of $5 trillion over 40 years. In a U.S. economy with $15 trillion per year, this indicates a relatively modest net positive economic impact compared to the business-as-usual path.
Finland	The report provides only limited cost analysis, based on expert assessment of individual sectors and technologies. It calls for further study of the precise economic impact of the model.

27 Natural Resources Canada, Important Facts on Canada's Natural Resources: Energy, last modified August 18, 2011, http://www.nrcan.gc.ca/statistics-facts/energy/895.

Country	Summary of Cost Treatment
France	The cost analysis focuses on annual energy expenditures, rather than the investment costs of the low-carbon scenario. It indicates total energy expenditure of € 79.8 billion in 2000, rising to € 144.4 billion in 2050 under a business-as-usual scenario. Under the F4 RCogN scenario, the energy expenditure would be € 67.4 billion in 2050, a saving of € 77 billion a year. This total rises to € 90.5 billion when potential energy price increases are considered, compared to € 239.4 billion in a BAU scenario. In addition to boosting emissions, the report states that sticking with a BAU approach would hamper economic growth and increase unemployment. While the report does not provide a detailed analysis of investment costs, it claims that these costs are offset by the rate of improvement in energy efficiency.
Germany	The study considers six potential price paths for fossil fuels. Under the Lead Scenario, and with a price path that assumes a constant rise in prices, initial investments in expanded renewable energy capacity are offset after 2020 (around 2015 with photovoltaics) compared to continuing reliance on fossil-generated capacity. After 2020, the cost comparison becomes increasingly favourable for renewables. The incremental cost of investing in renewables rises to € 5.2 billion per year in 2013, then begins to drop, and becomes negative by 2023. By 2030, these investments save the national economy € 7 billion per year, and the macro-economic cost saving reaches € 16.5 billion per year.
Sweden	The report does not provide a comprehensive cost analysis, but acknowledges the need to do so in the future.
UK	The UK study uses an optimization model in which a number of scenarios are developed against a common demographic and economic baseline. Carbon emissions are constrained at different levels, both annually and cumulatively, as are a number of other variables related to supply diversity, accelerated technology development, and various socio-economic and global uncertainties related to environmental impacts, perceived local impacts of new technologies, resistance to new technologies, and different assumptions with regard to global fossil fuel prices and carbon markets. The scenario used in our inter-country comparison involves constraining carbon emissions to 80 per cent compared to 1990 levels. Compared to business-as-usual, it results in increased energy system costs of 17 billion GBP and societal costs of 38 billion GBP. Most of the UK scenarios yield similar results. One variation of the 80 per cent reduction—the low-carbon lifestyle scenario—assumes that higher energy prices trigger a reduction in energy services demand, with a corresponding reduction in incremental energy system costs of 94 billion GPB compared to the reference case. The increase in energy system costs of 18 to 31 billion GPB that characterizes most of the scenarios compares with a total energy system cost of 250-300 billion GBP in 2050, so that decarbonization represents a system cost increase of about 10 per cent. Societal costs are about 3 per cent of current UK GDP (about 1.5 trillion GBP), and would be less than half of that by 2050, given the 2 per cent annual GDP growth assumed in the baseline.

Conclusions

The purpose of this review was to provide a deeper understanding of the current level of analysis and discourse in the low-carbon energy futures literature. We considered eight national studies with starting points comparable to Canada and an objective of cutting greenhouse gas emissions by 80 per cent by 2050. We identified common themes and trends, as well as limitations in the scope of the analyses.

Common Themes

- **Energy Efficiency:** Each of the scenarios relies heavily on extensive and rapid gains in the efficiency of fuel and electricity use, in all sectors. Improvements in efficiency are the primary means of reducing per capita final energy consumption, which converges in the range of around 100 GJ per person by 2050 across the studies (equivalent to the total per capita energy consumption of Germany or France today). The one exception is the UK study, which in conjunction with still impressive efficiency gains, also relies on the regulation of higher energy prices to trigger a reduction in demand for energy services. Per capita levels of fuel and electricity consumption start from much higher levels (about double) in the U.S., Canada, and Australia compared to the European countries (with the exception of Finland).

- **Electrification of End Uses:** Electrification of end uses, specifically in transportation and heating, plays a prominent role in all the scenarios. As the review shows, Canada has a low share of final energy demand supplied by electricity compared to the other countries we studied. The historical and economic reasons for this difference will warrant further research, as it poses both challenges and opportunities in developing a framework for a low-carbon energy future.
- **Decarbonization of the Electricity System:** Closely accompanying the emphasis on electrification is a universal emphasis on decarbonization of the electricity system, for which the various studies set out a number of paths. Each of the review scenarios increases the role of renewable energy in the energy supply, but the specific contributions of different types of renewables varies greatly. Similarly, there is no consensus on the role of low-carbon, non-renewable energy technologies. Four of the eight review scenarios present a future in which nuclear power has been completely decommissioned, while three show nuclear power contributing the majority of the carbon-free electricity (the remaining scenario, Sweden, does not specify what role, if any nuclear will have). Similarly, only two of the scenarios include a role for carbon capture and storage (CCS). In the UK study, CCS is the primary method of decarbonization in the early part of the scenario period. In the Swedish scenario, it contributes less than 10 per cent of the total CO2e reduction by 2050.
- **Increased Use of Biomass:** Increased use of biomass is the final common component running through all the strategies. While there is consensus that electrification will play an increasingly significant role through 2050, the studies suggest that electrification will not likely make up the majority of the energy end use pie—the Finnish scenario finishes with the highest percentage of electrification, at 51 per cent. Various forms of biofuels are used to decarbonize the majority of the remaining energy end use demand. Emerging from this is a general consensus on the need to expand the use of biofuels to what will be unprecedented levels. Given Canada's geography, it will be important to understand the limits on the volume of biomass the country can sustainably produce for energy. The Trottier Energy Futures project will further investigate the potential of biomass as a greenhouse gas reduction option in Canada by convening experts from across in the country in the next phase of our research.

Key Differences

As helpful as the common themes may be in illuminating factors that will likely play an important role in the TEFP scenarios, this review revealed important differences between Canada and the other seven countries considered. Canada is the largest geographically, it has one of the smallest populations and one of the coldest climates, and is the only net exporter of petroleum. This unique mix of economic, demographic, and biophysical (not to mention social and political) factors creates challenges and opportunities that are not easily comparable.

All eight countries have high-income, industrialized economies, yet their population growth rates, economic growth rates, energy use per capita, and greenhouse gas emissions per capita vary widely. We began this review by dividing the countries into two groups, the European group (UK, France, Germany, Sweden, and Finland) and the UCA group (United States, Canada and Australia). At the baseline (2009), European countries showed slower population growth, slower or even negative growth in greenhouse gas emissions, lower GHG emissions per capita, and higher decoupling of emissions and economic growth rates. Emissions intensities in the European nations, both per capita and per GDP, are significantly lower than in the UCA countries—compared to Canada, 40 to 75 per cent lower. With a common goal of a roughly 80 per cent reduction, this means that by 2050 the European countries will have emission intensities that are 90 to 95 per cent below the UCA group.

While there are many similarities between Canada, Australia and the U.S., Canada has a significantly different electricity profile. Though the three countries show similar percentages of electricity as a share of total final consumption, Canada has a much higher percentage of renewable energy (predominantly large-scale hydropower) contributing to overall electricity production, and therefore begins with a much lower carbon intensity than either Australia or the U.S. In 2009, Canada's carbon intensity was 71.5 kg CO2e/GJ, compared to 93.1 in the United States and 127.7 in Australia.

Limitations in Scope

To a large extent, the studies we reviewed defined the low-carbon challenge as one of large but still fundamentally incremental changes in the efficiency and carbon intensity of what are essentially “business-as-usual” futures. In this frame, the challenge of reducing energy-related greenhouse gas emissions is seen as one of internal adjustments to the mix of technologies and techniques that characterize the energy sub-system—more efficiency, and greater reliance on low-carbon supply resources. The demand for fuels and electricity, or at least the demand for energy services, is taken as a given, and is typically assumed to grow with population and economic output.[28]

The studies do show that a combination of aggressive efficiency and low-carbon fuel and electricity can result in greenhouse gas emissions that are in the range of 20 per cent of current levels, that such futures are technologically feasible, and that the economic impacts of their implementation are manageable. However, both the absolute levels and the rates of new technology deployment necessary to meet the 80 per cent emission reduction target by 2050 are large compared to historical experience. Per capita fuel and electricity use drop to the lowest levels in more than 100 years. The electric car, heat pumps, and other electrification technologies accelerate to market dominance by 2030. Net zero energy buildings become the norm no later than the 2030s, even as countries commit to relatively deep energy retrofits on existing buildings. The electricity grid is transformed. Biomass-based fuels grow from their current role as additives to become the primary source of liquid fuels for freight transportation, and in other applications where electrification is either not feasible or not affordable.

While all this change is going on in the energy sub-system, the rest of the economy and the society will also continue to evolve. We know from historical observation, as well as from the few examples in the studies we reviewed, that these changes in the wider economy affect the level and pattern of fuel and electricity consumption, as well as the resulting greenhouse gas emissions. These effects are equal to or larger than the impacts of the efficiency and low-carbon supply developments within the energy system. For example:

- Mobility needs and automobile dependence are largely determined by community design and urban form, but energy (and emissions) implications are rarely a significant design factor.
- Energy and fuel costs were trumped by more important factors that led to the steep rise in tonne-kilometres of freight movement in recent years, and the same is true for the modal shift from rail to road.
- Energy has become at least a secondary factor in the design of buildings in recent years. But even the green buildings trend is being driven by an interest in improving building comfort, aesthetics, marketability, and overall technical performance, based on a series of metrics that include but go well beyond fuel and electricity savings.
- The growth of the service economy and general manufacturing, and the drive to increase value added in the primary industries, have together done more to improve the energy productivity of the Canadian economy in recent years than all efforts to make the energy system more efficient.

In scoping the challenge of achieving a low-carbon energy future, it is important to include all three categories of factors that determine the level and pattern of energy-related greenhouse gas emissions: the root factors that lead to demand for fuel and electricity, efficiency of fuel and electricity utilization, and the carbon intensity of fuels and electricity.

Acknowledging energy services demand as a key driver of a low-carbon future is not the same as endorsing heavy-handed or top-down policies designed to restrict access or consumption. It is, rather, an effort to understand how energy services demand changes over time and identify trends and additional opportunities to reduce emissions. This requires that we approach energy as a subsystem that meets the specific needs of a much broader economy and social structure, and that we scope the question of how to achieve a low-carbon future in that broader context.

28 Our report discusses some notable exceptions to this definition of scope, particularly in the U.S., UK and Finnish studies. The exceptions, as far as they go, illustrate that factors such as demography, consumption patterns, housing preferences, supply chain organization, and economic structure have a powerful impact on emissions.

Appendix 1 – Summary Descriptions Of Country Reports

AUSTRALIA

Long Term Greenhouse Gas Scenarios, Australia Institute, 2002

Long Term Greenhouse Gas Scenarios was published in 2002 and was one of the earlier attempts to develop a comprehensive, national low-carbon scenario. The report targets a 60 per cent greenhouse gas reduction from 1998/1999 levels by 2050 (a total of 310 Mt of GHGs), leading to a per capita drop from 27.9 to 11.2 tonnes, but this includes all greenhouse gas emissions sources, not just energy-related sources. In achieving that result, energy-related emissions are reduced by 70 per cent (to offset the lower emission reductions deemed feasible for some of the other greenhouse gas emission sources in Australia, particularly in agriculture.) The study includes emissions from manufacturing, mining, commercial and residential sectors, agriculture, forestry, land use changes, construction, waste, and transportation, but excludes international aviation and shipping.

The report assumes 0.5 per cent annual population growth and real GDP growth of 2.25 per cent per year, more than a tripling in GDP over 50 years.

Australia's economy is quite resource-dependent (mining, petroleum, agriculture, and forestry), and the emission reduction scenario laid out in the report does not change that. However, certain sectors change considerably in the scenario. The study's emission reduction scenario assumes that, by 2050, Australia will phase out brown coal production and reduce black coal by 50 per cent, while allowing natural gas to grow in step with GDP. Electricity production shifts from large-scale thermal generators to distributed cogeneration and renewable power such as wind, which supplies 50 per cent of gross electricity in 2050 in the scenario that yields the deepest GHG reductions. (Photovoltaics remain a niche source, a result that likely reflects the limitations of a technology assessment conducted in 2002.) Australia's beef industry is assumed to grow with the rise in global demand.

An expected high reliance on biomass for energy in 2050 results in a substantial increase in forest plantations. Around eight million hectares of forest plantations are assumed to be available for bioenergy to supplement agricultural and food industry wastes as feedstocks. The authors note that the already significant biomass requirement doubles when the scenario target increases from a 60 per cent GHG reduction to 70 per cent. Non-resource sectors also shift, but more modestly, with expected growth in commercial and service sectors and declines in manufacturing.

The study does not investigate policy options for achieving significant reductions in GHGs and considerable shifts in Australia's economic make-up. Nor does it include behavioural change as a potential avenue for reducing emissions.

The major sources of emission reductions include:

- Increased energy efficiency, particularly cogeneration, supplemented by fuel switching and a shift to renewable energy in the industrial sector
- A turnover of the vehicle fleet, leading to a much greater share for newer technologies such as hybrids, fuel cells, and biofuels
- Improved building design, more energy-efficient equipment and appliances, and a switch to gas cogeneration in the residential and commercial sectors.
- Emission reductions from the agricultural, construction, and waste sectors, which are found to be feasible but more modest.

CANADA

Energy [R]evolution - A Sustainable Energy Outlook for Canada, Greenpeace International/ European Renewable Energy Council, 2010

The third edition of Energy [R]evolution, the Canadian component of a multinational study, assesses all energy-related sectors and models an 86 per cent and 94 per cent carbon reduction by 2050 from a 1990 baseline year. The more ambitious target involves GHG emission reductions of 476 Mt/year. Between 2007 and 2050, the model shows population growth from 32.9 to 44 million, or 0.68 per cent per year, with GDP growth at 1.77 per cent per year.

The study focuses on energy production and energy technologies, and so does not consider significant changes to energy-consuming industries in Canada. However, it envisions a considerably changed energy sector, with nuclear power, coal-fired power, and production from the oil sands phased out. Coal plants are assumed to shut down on a shorter timeline in the deeper emissions reduction scenario. Renewable energy—both heat and electricity—and cogeneration grow considerably to fill the void.

Energy [R]evolution dedicates a whole chapter to policy changes designed to address energy and greenhouse gas emissions. They include:

- Eliminating subsidies to fossil fuels and nuclear energy
- Implementing a cap-and-trade system
- Enacting energy efficiency standards for appliances, buildings, and vehicles
- Establishing targets for renewable energy
- Introducing a feed-in tariff that guarantees access to the grid and a set price for renewables
- Increasing research and development spending on energy efficiency and renewables.

The report recommends transportation demand management through government investment in public and non-motorized transport, better urban planning and limits to urban sprawl, and freight transport management. Proposed behavioural changes are confined to the transportation sector, including greater dependence on public transit, more active transport, a shift to smaller vehicles, and "teleworking."

A 94 per cent emissions target dictates significant reductions in all economic sectors. Emission reductions in electricity and heat are achieved through a combination of energy efficiency (a 44 per cent reduction in demand) and aggressive implementation of all cost-effective renewable energy. A 48 per cent reduction in transportation energy reflects the introduction of more efficient vehicles, modal shifts from road to rail, and behavioural changes described above. The electrification of vehicles plays a major role in reducing transport emissions. Use of biofuels is severely limited through strict criteria for their development.

A sustainability screen is also applied to constrain large hydropower development. Carbon capture and storage is ruled out due to its anticipated high cost.

FINLAND

Government Foresight Report on Long-term Climate and Energy Policy: Towards a Low Carbon Finland, Prime Minister's Office, 2009

Finland's Foresight Report uses a spreadsheet-based analysis to map an 80 per cent carbon reduction relative to 1990 emissions, reductions that would total at least 65 Mt per year by 2050. Though the focus of the paper is on energy, most of Finland's economic sectors are considered: industry, transportation, energy generation, heating, waste management, and agriculture.

The report's four scenarios reflect differing assumptions about the contributions of various energy efficiency and supply strategies, as well as important parameters such as economic growth (varying from 1.2 per cent to 1.8 per cent GDP growth per year), regional and urban structure, housing types, volume and type of personal and freight transportation, level and type of agricultural output, and energy demand and production. The scenarios make vastly different assumptions about the future structure of the Finish economy, ranging from:

- A future economy that is essentially the same as the current one, to
- A country that shifts markedly away from industry and towards the service sector, to
- A Finland that is self-sufficient in everything from energy to food.

All the scenarios presume population growth of 0.17 per cent per year.

The scenarios entail significant differences in the behaviour of the Finnish population, incorporating a variety of assumptions about housing preferences (including whether people have cottages or second homes); transportation choices for local, regional and international travel; and even values and lifestyle issues such as vegetarianism and the amount of leisure time. The policies to achieve different energy sector and societal outcomes are not explored.

All the scenarios achieve the 80 per cent reduction target. Two of them (one focused on energy efficiency, one on nuclear power) approach or reach 90 per cent reductions. In order of importance, the strategies to reduce emissions for Finland include:

- High levels of energy efficiency in both new and existing buildings
- Continued and intensified use of combined heat and power, including waste heat from nuclear power plants in the scenarios that include nuclear
- Maximizing renewable and zero-carbon energy sources (nuclear, CCS)
- Introducing energy-efficient vehicles and electrification
- Reducing transportation demand and placing greater emphasis on more sustainable modes of urban development that require less mobility
- Introducing low-emission solutions in industrial processes
- Shifting food production and consumption toward low-emission options.

Table 11. Summary of Finnish Low-Carbon Scenarios

	A. Efficiency Revolution	B. Sustainable Daily Mile	C. Be Self-Sufficient	D. Technology is the Key
Average economic growth	1.7%	1.8%	1.2%	1.8%
Economic structure	Very strong growth in service sector. Traditional metals and forest industry replaced by new products and knowledge industries (eg. nano, bio, IT). Renovation of buildings.	Modest growth in service sector share of GDP. Demand for mass consumption products decreases; more individual products and services. Renewal of industries, biorefineries, IT, recycling. Ecological construction an export product.	Slight increase in share of service sector. Forest industry becomes bioindustry. Strong domestic food industry. Energy self-sufficiency supported by new construction, renovation, and building with wood.	No change in structure. Energy-efficient knowledge industry (IT, bio, nano, etc.) in south, natural industries outside urban areas. CCS in process industry.
Urban structure	8-12 strong regional centres, cohesive urban structure.	Decentralized regional structure, service centres surrounded by efficiently built areas.	20 strong regional centres, dispersed urban structure.	Regional structure concentrated in south, compact cities surrounded by dispersed structure.
Transport	Per capita travel declines, goods transport at base year level, cars double in efficiency, biofuels and electricity.	Private cars in rural areas, transit in and between urban areas. Goods transport declines. Short trips by foot and bicycle.	Passenger traffic in and between cities by rail and hybrid biobuses. Cars on biofuels and electricity. Less international traffic.	Increase in personal travel, shift to electric cars. Increased goods movement. Public transit in congested corridors, intercity high speed rail.

	A. Efficiency Revolution	B. Sustainable Daily Mile	C. Be Self-Sufficient	D. Technology is the Key
Final energy consumption	Reduced by 50%, radical improvements in efficiency in all sectors. Strong demand response, trigeneration (electricity, heating, refrigeration).	Reduced by 25%, but industry at roughly present level. Less energy needed for transport and housing. Consumption electrified.	Reduced by 33%. Homes in low-density areas produce their own energy. Slight decline in personal consumption and travel.	Maintained at present level. Increased consumption by industry and transport. Intelligent household appliances and electric cars. Consumption electrified.
Renewable share of energy supply	100% renewable, with biomass and wind the most important sources. International energy trade, eg. wind power from the North Sea (super grid).	Two-thirds renewable. Condenser water from nuclear power plants used for heating.	80% renewable, with decentralized small-scale production, new hydropower, bio-CHP, CCS-peat.	60% renewable, with steep increase in nuclear power, including fast breeders. Fossil fuels and peat in large CCS facilities.
Nuclear power	Phased out	Doubled over current level	Halved	Tripled
GHG reductions compared to 1990	90%	80%	80%	90%
Emissions from cars, in g CO2/km (163 g/km in 2010)	112	42	8	0
Utilization of biomass	Domestic reserves more than adequate	Domestic reserves fully utilized	Domestic reserves fully utilized	Domestic reserves fully utilized, plus imports
Carbon capture and storage	No	No	Yes, in association with peat production	Yes, for both fossil fuel power plants and peat production.

FRANCE

La division par 4 des émissions de dioxyde de carbone en France d'ici 2050, Mission Interministérielle de l'Effet de Serre, 2004

La division par 4 sets an overall carbon target of 0.5 tonnes per citizen in 2050, as a basis for cutting emissions 75 per cent (or 283 Mt) against a 2000 baseline year. The study projects business-as-usual emissions based on 1.7 per cent annual GDP growth and a 2050 population of 64 million, a 0.11 per cent annual growth rate, then simulates the reductions that would be required in specific sectors—steel production, other industries, residential and commercial buildings, agriculture, and transportation—to meet the Factor 4 objective.

With respect to GHG emissions, industrial sectors in France are notable for a couple of reasons. First, there is an absence of oil production, and natural gas provides only a tiny fraction of domestic demand. Second, electricity production in France is dominated by nuclear power. The report does not envisage major changes to France's industrial sectors by 2050.

No growth is assumed in the steel industry, while other industries are expected to grow by 1.2 per cent per year.

The report suggests policy changes that would help drive emission reductions. A price on carbon is considered essential, with preference for market mechanisms such as cap-and-trade. The study also suggests more compact urban planning and building codes with much more stringent energy efficiency requirements. Finally, public expenditures are reoriented towards public transit and other sustainable infrastructure. The report touches on behavioural changes that would be required, but only in transportation, including using more public transit, driving smaller vehicles, and choosing rail over air travel, especially for short and medium distances.

The report identifies natural gas cogeneration and energy efficiency as essential activities to achieve significant emission reductions. Before factoring in any energy cost increases subsequent to 2000, the study suggests savings of € 77 million that would be available through energy efficiency. Beyond these factors, five different approaches all yield similar reductions and allow France to reach its Factor 4 target. These different approaches are:

- Significant expansion of nuclear power
- Balancing nuclear power with cogeneration and renewables
- Continued reliance on fossil fuels, with carbon capture and storage
- A phasing out of nuclear power, with even greater emphasis on carbon capture and storage
- Reliance on hydrogen systems and technologies, using nuclear power as the energy source.

Beyond investments in energy efficiency and cogeneration, the greatest potential for emission reductions appears in the transportation sector, the area with the highest emissions in 2000, but emission reductions vary across the scenarios. The scenarios that include nuclear power offer the greatest emission reductions in transportation, through electrification. The residential sector has the second-greatest potential for emission reductions.

GERMANY

Lead Study 2008: Further Development of the "Strategy to Increase the Use of Renewable Energies" Within the Context of the Current Climate Protection Goals of Germany and Europe, German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety, 2008

Lead Study 2008 assesses energy-related sectors to develop a scenario where an 80 per cent carbon reduction from a 1990 base year can be achieved by 2050. The target actually achieved in the report is a reduction of 625 Mt of GHGs per year from 2005 to 2050, equivalent to a 78.4 per cent reduction, based on 1990 emissions. The study includes all energy-related GHG emissions plus process emissions from blast furnaces.

The report assumes that Germany's population will fall from 82.4 million in 2006 to 75.1 million in 2050 (a -0.6 per cent growth rate per year), and that GDP will grow by 1.14 per cent per year, or 64.9 per cent over the study horizon. To meet the 78.4 per cent target, GHG emissions will have to decline from 10.2 to 2.8 tonnes per capita.

The study models the impact of three specific strategies: expanding reliance on renewable energy, maximizing energy efficiency, and expanding cogeneration to improve the efficiency of fossil fuel plants. Because the focus of the study is on energy, no significant changes in Germany's energy-consuming industries are anticipated. In the energy sector, however, significant changes are assessed, including a phasing out of nuclear power. Climate change policies also reduce fossil fuel industries and increase the biomass energy sector, though biomass development is constrained by a cap on the land available for biomass production and a requirement that no food production be displaced.

The modeling is driven by energy and GHG policies, and by policy commitments made by Germany on a 2020 horizon. By that year, Germany expects to meet 30 per cent of electricity sector demand (14 per cent of heating, 12 per cent of fuels) with renewable energy, double energy productivity, and reduce GHGs 20 per cent from a 1990 baseline. An additional package of GHG emissions measures adopted by the German government in June, 2008 is also factored into the analysis. Though the study calls for a consistent, dedicated policy agenda to 2050 to deliver the necessary emission reductions, specific policies are not considered as drivers for reductions beyond 2020. Behavioural changes are not considered at all.

Through 2020, the greatest reductions are derived from expanded renewable electricity generation and improved efficiency in heating, primarily space heating. Post-2020, renewable electricity dominates, followed by efficiency in heating and greater use of renewables for heat. Beyond these three activity areas, the study attributes equal importance to the expansion of renewable fuels, efficiency improvements in electricity generation, and efficiency improvements in transportation.

From 2020 to 2030, renewable energy grows to 50 per cent of electricity supply. Primary energy productivity continues to improve at a rate of 3 per cent per year, largely through expanded cogeneration and replacement of older power plants with newer, more efficient technology. By 2050, renewables account for nearly 50 per cent of primary energy production. Germany only requires 37 per cent of the fossil-based energy production that was deployed in 2005, and energy imports decrease by 60 per cent.

SWEDEN

Swedish Long-Term Low Carbon Scenario: Exploratory Study on Opportunities and Barriers, Swedish Environmental Research Institute, 2010

The Swedish Long-Term Low Carbon Scenario is a national study that tests the feasibility of eliminating all use of fossil fuels in Sweden by 2050, working from a base year of 2005. The analysis covers all industrial sectors (iron and steel, minerals and cement, petroleum refining, pulp and paper, mining, and manufacturing), residential and commercial buildings, all modes of transportation, specific land uses (agriculture, forestry, fisheries), electricity production, district heating, and services (including municipal utilities).

The primary scenario in the study focuses on reducing all fossil fuel use where technically possible, leading to heavy reliance on biofuels in transportation and for district energy. Emissions are reduced by 47 Mt, or 79 per cent. The second scenario allows for continued fossil fuel use in transportation, offset through carbon capture and storage, resulting in a 72 per cent reduction in GHGs.

The study incorporates official government projections of 17 per cent population growth and 2.25 per cent annual GDP growth from 2005 to 2050. Energy efficiency is assumed to increase by 3.45 per cent per year.

The economic make-up of Sweden is not assumed to change much in the emission reduction scenarios. All industrial subsectors grow at the rate of economic growth, with the exception of the very small petroleum refinery sector, which is phased out by 2050. The electricity sector is only slightly larger in 2050 (greater economic activity is offset by improved energy efficiency), but the report suggests the possibility of a nuclear phase-out, with that generation capacity replaced by renewable energy production, including wind and hydropower.

Because of the report's focus on phasing out fossil fuels (as opposed to reducing greenhouse gas emissions), information related to the major sources of emission reductions is lacking. Required policies and behaviour changes are not discussed in separate chapters, but are referenced throughout the text. The major activity leading to emission reductions is the switch from fossil fuels to bioenergy across all sectors. Other renewables, such as solar heat, play a smaller role, though they may have been more prominent had a different electricity mix been specified. Carbon capture and storage is found to have great potential, totalling up to 20 Mt of GHG reductions by 2050 (close to half the total in the scenario that focused on this option).

UNITED KINGDOM

Energy 2050: Making the transition to a secure low carbon energy system, UK Energy Research Centre, Earthscan, 2011.

The low-carbon scenario analysis conducted under the auspices of the UK Energy Research Centre was carried out over a period of five years, from 2004 to 2009, to address two of the UK's energy policy goals: ensuring supply resilience in meeting energy demand, and reducing greenhouse gas emissions by 80 per cent by 2050, relative to 1990.

The project relies heavily on the use of interlinked models, including the energy systems UK MARKAL Elastic Demand model, as well as sectoral models in the electricity and gas sectors (CGEN, WASP) and end-use buildings and transport sectors (UKDCM, UKTCM). The MARKAL model (the acronym is derived from "MARKet ALlocation") employs linear programming methods to identify the least-cost mix of energy supply, demand, and CCS technologies to meet a particular set of constraints. One of the objectives of the project was to enhance the UK's capacity for comprehensive energy and energy policy analysis and modeling, and the research team spent three years developing the version of MARKAL that was used to generate the long-term energy scenarios.

The study includes a reference scenario and 31 scenario variations. The results used for the inter-country comparisons in this review are taken from the core low-carbon (LC) scenario, which includes an 80 per cent reduction in greenhouse gas emissions, relative to 1990, by 2050.

The MARKAL-MED model includes price elasticities of energy services demand, an innovative approach to estimating the decline in energy services (and corresponding societal costs) that could be triggered by the fuel and electricity prices associated with deep carbon reductions.

Greenhouse gas emissions grow only slightly in the reference scenario in the UK analysis, by about 6 per cent by 2050, with declining emissions in residential and commercial buildings offset by growth in power sector emissions. By 2050, the power sector accounts for 45 per cent of total energy-related greenhouse gas emissions in the UK reference scenario, reflecting the continued use of coal. In the LC and other carbon reduction scenarios, decarbonization of the power sector dominates the model response, especially in the early years of the scenario period. By 2050, power sector emissions are reduced by 93 per cent compared to the corresponding level of emissions in 2050 in the reference scenario. The corresponding reductions for the residential, transport, services, and industrial sectors are 92, 78, 47 and 26 per cent, respectively. In addition to efficiency improvements, reductions in energy services demand contribute to lower emissions across all sectors, but are most pronounced in the residential and industrial sectors (up to 20 per cent demand reductions).

In addition to decarbonization of the power supply through CCS, nuclear, and wind, the lower carbon intensities result from a shift in the residential sector from gas boilers to electric heat pumps, in the transport sector to hybrid plug-ins, ethanol, hydrogen, and battery-electric vehicles, and in the service sector to biomass.

Table 12. Energy Scenarios from UKERC's Energy 2050

Short Form Name	Scenario	Brief Description
REF	Reference	Incorporates policies as of the UK 2008 Energy Bill, but no CO_2 price
LC	**Low carbon, CAM (carbon ambition)**	**Emissions constrained to 118 Mt CO_2e in 2050, 80% below 1990 levels**
LC-40	Faint heart (CFH)	Emissions constrained to 355 Mt CO_2e in 2050, 40% below 1990 levels
LC-60	CLC	Emissions constrained to 237 Mt CO_2e in 2050, 60% below 1990 levels
LC-90	CSAM – Super ambition	Emissions constrained to 59 Mt CO_2e in 2050, 90% below 1990 levels
LC-EA	CEA – Early action	Emissions constrained to 118 Mt CO_2e in 2050 (the 80% target) but with accelerated early action to reduce emissions by 32% by 2020
LC-LCP	CCP – Least-cost path	Same cumulative emissions as with LC-EA, but with a least-cost cumulative path
LC-SO	CCSP Socially optimal least-cost path	Same cumulative emissions as with LC-EA, with a least cost cumulative path, and a 3.5% social discount rate
R	Resilient	No primary source with market share above 40%; 40% maximum market share per technology class in electricity generation
LCR	Low carbon resilient	Combine LC and R scenarios

Short Form Name	Scenario	Brief Description
LC-Acctech, LC-Renew, LC-60 Acctech, LC-60 Renew, LC-60 Bio, LC-60 Nuclear, LC-60 FC, LC-60 Marine, LC-60 PV, LC-60 Wind	accelerated technology scenarios	Variations on the LC-60 scenario in which the deployment of technologies is accelerated via exogenous technology narratives specifying performance and cost breakthroughs
LC-DREAD	DREAD	Constraints on unfamiliar technologies: 10 GW onshore wind, 80 GW offshore wind, no tidal barrage, 30.4 GW nuclear, 10.5 GW CCS, biomass at 37% of reference scenario and restricted to transport only
LC-ECO	ECO	Constraints on onshore wind (10 GW), offshore wind (80 GW), no tidal barrage, 13.5 TWh partial stream, 37.5 TWh per annum wave. Domestic biomass at 11% of REF and restricted to heat and power, no imported biofuels, high fossil fuel prices
LC-NIMBY	NIMBY	No nuclear, no CCS, no hydrogen
LS-REF	Reference lifestyle	Lower building set temperatures, drop in hot water use, decreased electricity for lights and appliances, full penetration of residential retrofits, take-up of district CHP to 25% by 2050, micro CHP up to 60% by 2050, solar thermal on 50% of buildings, solar PV on 15% of buildings, mode shift of 75% reduction in VMT, increased bus travel, cycling, walking; reduced hurdle rates for electric and hybrid cars
LS-LC	Low carbon lifestyle	LS-REF with 80% CO2 reduction
LC-HI, LCR-HI, OC-CC, LCR-CC, LC-HI-LC, LCR-NB	Global sensitivities around the LC and LCR scenarios	Variations include high fossil fuel price imports, central cost credits, no biomass imports

UNITED STATES

Reinventing Fire: Bold Business Solutions for the New Energy Era, Amory B. Lovins and the Rocky Mountain Institute, Earthscan 2011.

Reinventing Fire is a comprehensive project that describes a suite of actions the United States can take to drastically reduce dependence on fossil fuels by 2050. The report does not outline specific energy or emissions targets it must achieve—instead, it evaluates what is technically and economically feasible to minimize fossil fuel use and reduce total energy use. The report describes specific technological possibilities, such as improvements in automobile production, fuel switching in industrial processes, and building designs and technologies that reduce direct energy consumption. Although Reinventing Fire is not specifically described as an attempt at a low-carbon scenario, it sets a course to reduce GHGs by more than 80 per cent from 2000 levels.

Using the U.S. government's Energy Information Administration official energy outlook as a baseline (extrapolated to 2050, since the EIA outlook concludes in 2030), the project's basic methodology is to thoroughly evaluate the energy needs of important fossil fuel-consuming sectors (industry, transport, buildings and electricity), then apply three principles:

- Reducing waste and maximizing efficiency

- Modulating or diversifying energy production
- Switching to renewable fuel sources.

While these principles are described separately, they are largely integrated in the different actions to reduce energy and emissions.

In each sector, the report looks at broad opportunities to reduce energy use while delivering the same or better levels of energy services. Project analysts evaluate technologies applicable to each sector and describe their performance. Alternative models of energy provision are evaluated to see if additional, system-level energy savings can be achieved. These alternative models include micro-grids, different growth models for cities, and integrated building design. This type of analysis is unique among the major low-carbon studies, in that it embraces integrative and systems-level thinking about the drivers of energy use and the opportunities to optimize efficiency.

Reinventing Fire argues that America's over-reliance on fossil fuels makes it a matter of economic necessity to build greater energy efficiency and independence. The report outlines the potential for capital and operating cost reductions, as well as the prospect of improved system resilience through decentralized grids, integrative design, and systems-level actions.

Out of this framework, Reinventing Fire sets sector-level goals for fossil and total energy demand reductions, the opportunities for businesses if they adopt these actions, and the total potential savings to the country, and outlines key actions in each sector for policy-makers and stakeholders.

Appendix 2 – Additional Low-Carbon Studies

Appendix 2 contains a list of low-carbon studies that were reviewed but did not meet the established criteria as explained in the introduction of this paper. Nevertheless, there is value in each of these studies, and further research may benefit from this reference list.

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