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Forest Residues to Energy: Is this a pathway towards healthier communities?

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Summary

- Forest residues are non-merchantable woody biomass found in forests and wood waste from logging practices and industrial operations, such as sawmills. Forest residues are a convenient fuel for open-burning and conventional biomass burning systems (e.g., fireplaces and wood stoves), but more recently have been considered as a fuel for advanced wood combustion (AWC) integrated energy systems, used for electricity production in addition to heating.
- AWC systems are defined as wood-fired high-efficiency automated energy systems with air pollution controls. Favored for use in Europe, they supply heating at economically achievable conditions, use wood resources efficiently, and can be an integral part of district energy systems.
- Emissions from open-burning and conventional biomass burning systems may contain such air contaminants as carbon dioxide (CO_2), elemental carbon, polycyclic aromatic hydrocarbons (PAHs), benzene, aldehydes, polychlorinated dibenzo-P-dioxins (PCDDs), and free radicals, as well as particulate matter (PM). In comparison, emissions of PM, carbon monoxide (CO) and volatile organic compounds (VOCs) from advanced wood combustion (AWC) systems, such as gasification, are considered to be an order of magnitude lower than conventional combustion systems.
- The quantity and chemical composition of airborne pollutants emitted from biomass burning depends on combustion characteristics and operating conditions, such as complete combustion, more likely with AWC systems, which leads to lower levels of pollutants and likely lower toxicity. Hygroscopicity (ease of absorbing water) is an important characteristic of PM originating from complete combustion, which reduces the probability of PM deposition in lungs, and therefore PM induced toxicity.

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- District heating systems, as an application of AWC, may increase health risks for local populations due to their proximity to emission sources.
- Since these systems are rapidly growing in Canada, more epidemiological and experimental studies are needed to evaluate the population health impacts of adopting AWC systems.

Introduction

Energy demands are an issue with growing populations and development. In order to secure energy supplies in a sustainable way, indicators such as greenhouse gas (GHG) emissions, land and water use, availability, efficiency, costs, and social implications need to be considered.[1] A most important outcome to be determined is the health of the population affected. Advanced wood combustion systems (AWC), defined as wood-fired high-efficiency automated energy systems with air pollution controls, are widely used in Europe. AWC systems may be attractive for implementation in North America for heating at economically achievable conditions, allowing more efficient use of wood resources and through means of district energy systems.[2] An integrated assessment approach, which implies simultaneous evaluation of system performance, characterization of emissions, and consideration of exposure scenarios, is suggested in order to evaluate potential health effects from exposure to AWC emissions due to the proximity of such systems to population centres.[3]

Based on a review of published literature, government documents and conference proceedings (search methods are provided in Appendix A), this document summarizes current knowledge on exposure characteristics and potential health impacts resulting from using forest residues as a fuel source for energy generation. This document is intended for policymakers who need to make informed decisions on biomass energy choices.

What are forest residues?

Biomass in its broadest definition includes all living matter, such as plant material, and vegetation and agricultural waste that could be used as a fuel or energy source.[4]

Forest residues refer to a non-merchantable woody biomass, such as tree species and residues from logging practices, including roadside and in-forest wood. In addition, forest residues from industrial operations, such as mill wood waste (sawdust, shavings, bark), are commonly considered as woody biomass - convenient for use as a fuel or energy source.

Biomass energy sector

Non-hydro renewable sources account for 1.6% of Canadian total electricity generation,[5] of which 60% is attributed to generating capacity from renewable biomass alone.[6] In the U.S.A., biomass plants are used for electricity generation for less than 1% of the grid.[7] In contrast, European countries such as Germany, U.K., Finland, and Sweden were the largest producers of electricity generated from woody biomass in 2005.[8,9] Finland, for instance, has achieved biomass-based electricity generation of about 11% (9) to 20%[10] of its total electricity consumption and has already developed bioenergy-based technologies from the forest industry sector.[11]

More than 400 million hectares of Canada's land (44%) are forests; most under provincial jurisdiction. The largest user of biomass (mostly forest residues) for energy is the Canadian forest products industry which generates almost 60% of its energy from this renewable source.[6] An Inventory of the Bioenergy Potential of British Columbia[12] identifies forest residues from industrial operations, such as mill wood waste (sawdust, shavings, bark), and forest residues from logging practices, as significant woody biomass resources in British Columbia. Other studies evaluated pine beetle damaged wood as an additional forest residues-type of feedstock for energy[13] and considered its impacts on the forest sector and province's economy.[14]

Biomass to Bioenergy Conversion

The use of biomass for energy is not a novel idea; however, it was often perceived less convenient for handling, transport, storage and processing than fossil fuels, expensive, and variable in net energy yields and land use requirements.[15] On the other hand, biomass is a renewable resource and close to carbon neutral (balance between plants' intake and emissions of carbon dioxide), which makes it attractive for energy use when addressing climate change in challenging times. Forest residues are being combusted in many ways – from open-burning, that commonly involves uncontrolled forest fires, land clearing burning, prescribed burning, and household burning in stoves and fireplaces, to industrial advanced integrated energy systems for heating and electricity or even commodity chemicals production.[16,17]

The main woody biomass to bioenergy conversion pathways are described below[18]:

Direct combustion refers to the process of fuel (biomass) oxidation resulting in heat as a primary energy product. Biomass can be processed to take the form of small pieces, briquettes, pellets and similar which improves the quality of feedstock in terms of reduced moisture, concentrated energy, ease of handling and transportation, and lower emissions of air pollutants. In industrial conditions, heat can be directed to turbines to drive generators for production of electricity.

Pyrolysis is a process of converting biomass into primary products: bio-oil, char, and syngas under high temperatures (around 700°C), and absence of oxygen. Syngas (synthesis gas) is further used in energy recovery systems for heat and power generation or through product recovery processes for synthesis of different chemicals.

Gasification is a process of thermochemical conversion of biomass into flammable gas mixtures known as "producer gas" (synthesis gas) at high temperatures of 750°C to 850°C and with leaner than stoichiometric oxygen supply. Producer gas can be further used for heat and power generation but also as a feedstock for production of fuels and chemical products.

The status of development and utilization of biomass technologies

Cogeneration of heat and electricity, known as Combined Heat and Power (CHP) biomass combustion-based systems, is an economical option which has been advanced in recent years. Such systems have already been commercially implemented for medium- and large-scale applications, such as district heating systems, wood industries, and industries with a high process demand with respect to heat and cooling.[8,19] More specifically, for large-scale CHP plants generating more than 2000 kW[(b)] of electric power, *the steam turbine process* (a process that converts thermal energy from steam to mechanical energy to drive an electrical generator) is prevalent. An *Organic Rankine Cycle (ORC),* a steam engine that uses heated vapour of an organic chemical instead of steam, is a technology applicable for medium-sized plants generating between 200 and 2000 kW of electricity based on biomass combustion[8] and is a promising technology for micro-CHP plants producing a few kW of electricity.[20]

Gasification-based biomass systems are still mainly applied as pilot or demonstration projects.[8,9] Biomass Integrated Gasification Combined Cycles (BIGCC) technologies are entering the market as a promising technology with respect to economic and technical performances.[9,21]

Small-scale distributed electricity generation (DG) technologies, configured as a number of small-scale distributed plants rather than conventional large-scale centralized power plants, have been promoted in order to meet local energy demands. These technologies include fuel cells, microturbines, internal combustion engines, and turbines.[22] Other technologies are also available, such as co-firing in conventional fossil-fuel power plants[23] or biomass mixtures with densified woody biomass (e.g., pellets)[24] and polygeneration system (an integrated energy system where a variety of products such as: heat, electricity or even chemical products are simultaneously produced).[16]

Air Emissions, Exposures, and Health Impacts from Woody Biomass Conversion

Forest residues are considered the most competitive source of bioenergy and an economically attractive option for further investments, because of the predicted lower production cost of biomass-based electricity when integrated in industrial forestry processes, as shown in European studies.[11] Nonetheless, there are challenges associated with biomass-related emissions. Some studies pointed out that chemical composition of emitted pollutants can vary with tree species burned.[25] Biomass feedstock composition plays a role in emissions and subsequent health impacts; industrial bio-wastes have higher levels of sulphur oxide and nitrogen oxide emissions than forest feedstock. When used, forest residues can lead to cleaner conversion with lower pollution levels and higher process efficiency than industrial and municipal bio-wastes, resulting

[(b)] kW - kilowatt

in potentially lower toxicity of emitted pollutants. However, there is evidence that quantity and chemical composition of airborne pollutants emitted from biomass burning will also depend to a large extent on the combustion technology and operating conditions, as discussed below.

Emissions Characterization

Conventional and open burning

Emissions resulting from incomplete combustion, such as forest fires, household fireplaces, and wood stoves are well documented in the scientific literature.These emissions may contain particulate matter (PM), oxides of sulphur (SOx), nitrogen oxides (NOx), carbon dioxide (CO_2), polycyclic aromatic hydrocarbons (PAHs), benzene, aldehydes, carbon monoxide (CO), formaldehyde, Polychlorinated dibenzo-P-dioxins (PCDDs), and free radicals.[26,27] Burning solid fuels, such as woody biomass in household cookstoves (as practiced in some developing countries), results in a variety of pollutants and Products of Incomplete Combustion (PICs), with some being carcinogens.[27,28] Data from the United States Environmental Protection Agency (US EPA) indicate that average emissions of fine particles are lowest for gas furnaces (0.0083 lb/MMBTU heat output), 40 times higher for pellet stoves (where emission of PM will be inversely proportional to the fuel load),[25] and up to 2000 times higher for wood burning fireplaces.[29]

Biomass as an energy resource is attractive because of its potential to help achieve climate policy targets[30] due to lower GHG emissions when compared to fossil fuels. However, an issue with biomass burning (combustion), particularly under uncontrolled combustion conditions, is the generation of black carbon (BC), which is a product of incomplete combustion that absorbs solar radiation. When combined with other radiation absorbing short-lived species, such as ozone, BC may contribute almost as much as carbon dioxide GHG emissions.[31,32] In order to estimate net BC climate impact, an offset by solar radiation reflecting species, such as co-emitted organic carbon (OC), sulphates (SO_4), and nitrates (a product of atmospheric photochemistry), should be considered.[32]

Evidence shows that quantity and chemical composition of airborne pollutants, emitted from biomass burning, will depend to a large extent on combustion characteristics and operating conditions; complete combustion (higher than stoichiometric level of oxygen) leads to lower levels of pollutants and likely lower toxicity. In industrial boilers, where combustion conditions are controlled (temperature, and amount of air or air/oxygen available for combustion), emissions of PM can be decreased providing the flue gas is cleaned in order to comply with specific emission standards.[33] Smaller, high temperature combustors, with refractory-lined chambers, will minimize particle emissions as opposed to large fluidized-bed combustors which add some silica particles (worn from the sand bed) to their total emissions.[33] Also, in an experimental study, emissions of PM associated with wood chip burners were found to be largely dependent on burner operating conditions, such as level of combustion air supply; too low or too high combustion air levels result in emissions of larger particles at increased concentrations.[34] Improvements in woody biomass characteristics (e.g., moisture content and uniform fuel quality, such as pellets) and complementary boiler designs can lower emissions of particles by 80% as compared to older firewood boilers.[35]

Wood smoke particles include organic carbon (hydrocarbons and derivatives), soot (elemental carbon and condensed organics), and inorganic ash (alkali salts) categories based on physicochemical characteristics and combustion conditions.[35] Particles from incomplete combustion (as evaluated for wood pellet burners) are more complex in composition with organic (carbon-based) content of about 85% and are relatively large in size as compared to particles from complete combustion with carbon content less than 1%.

Elemental and inorganic-phase particle distributions are predominantly in a submicron range and are typically composed of potassium, sulphur, and chlorine while with bark burning potassium and sodium predominate.[36-39] The amount of inorganic fine PM is associated with ash-forming elements during combustion and during the cooling stage of flue gas.[25] These findings are in agreement with other studies which claim that dry wood, such as shavings, wood chips or pellets when combusted, will contain potassium and sulphur in emitted submicron-sized particles and calcium in a coarse fraction of emitted particles.

Advanced Wood Combustion Systems (AWC)

Gasification converts solid fuels into combustible gases, such as methane (CH_4) or syngas [a mixture of hydrogen (H_2) and carbon monoxide (CO)] through a series of interconnected reactions. Recent studies[40,41] showed that improvements in technology, such as gasification through decoupling reactions (i.e., controlled individually), can significantly improve gasification process efficiency by optimizing reactions, resulting in better product (syngas) and reduced emission levels, including sulphur (with use of coal as a fuel) and nitrogen.[42] One study concluded that emissions of sulphur dioxide (SO_2), nitric oxide (NO), benzene (C_6H_6) and toluene (C_7H_8) can be detected if a biomass fuel mixture contains more industrial waste-products, such as olive pomace (olive waste), than forest residues. Co-combusting biomass with coal to produce electricity reduces CO_2, NOx, and SOx[8,43,44] even with a biomass to coal fuel ratio as low as 10% on a heat input basis.[23]

Recent studies examined types and characteristics of air pollutants from AWC systems, such as those based on gasification-based technologies. Emissions of PM, CO, and VOC from such AWC systems are considered to be an order of magnitude lower than from conventional direct combustion systems.[45] However, in order to meet air quality standards and ensure protection of human health, installation of engineered pollution-control devices are needed specifically for PM.[46]

The net benefits of switching to biomass as a fuel also depend on which fuel is going to be replaced. For example, if evaluated over the entire life cycle, replacing a natural gas boiler with a biomass gasification system will result in reduction of generic CH_4 and CO_2 of fossil origin. However, there will be increased emissions, especially of PM and NOx in the biomass gasification stage (a high temperature process favours formation of NOx), which can be reduced with pollution controls in place. Over the entire life cycle, the harvesting stage of wood for gasification (which does not exist with natural gas utilization) still remains the main contributing stage of PM and Nox.[45]

Exposure and Health Implications

Conventional and Open Burning

Health effects resulting from exposure to wood open-burning emissions have been extensively studied over the years. Several earlier review publications addressed health implications due to exposure to woodsmoke. For example, Naeher et al.[26] summarized the literature findings on emissions, exposure, and health effects (encompassing epidemiological, toxicological, control human exposure, and occupational studies) resulting from forest fires, agricultural burning, and residential woodsmoke in developed countries. PM was found to be the most consistently elevated airborne pollutant of all emissions from burning biomass, reaching even 3 to 4 times higher concentrations during vegetation fires than during nonfire periods. Fine PM can be transported over great distances from the fire location. The same pollutant is identified as a major contributor to deteriorated outdoor air quality, especially during winter months as a result of residential wood burning. Some case-control studies estimated that PM indoor concentrations were almost five times higher in homes using wood for heating than in those using gas or electricity.

Chemical composition and size distribution of particles from biomass burning is of particular interest as particles are often used as the best single indicator of combustion-induced health impacts.[26] With respect to the PM size, smaller particles (below 2.5 micrometer) can penetrate deep into the lungs and even the bloodstream. Reduction in fine particles and consequently reduction in BC and organic carbon (OC) levels have important health implications as, according to some studies, lower levels of these pollutants can reduce premature mortality.[31] Overall, the scientific studies indicated that both exposure and duration of outdoor and residential woodsmoke resulted in a variety of increased respiratory symptoms, emergency visits, and hospitalization.[26] Mortality was associated with extremely high PM levels from bush fires.[46] Smoke-derived PM levels resulted in increased severity of ongoing disease processes.[39] However the composition of PM differs from that emitted from fossil fuels (most commonly used for health studies), which indicates potentially lower toxicity of PM originated from biomass than from diesel, for example.), However, more investigation into biomass-specific emission characteristics is needed in order to evaluate their relative toxicity and health impacts.[47,48]

Although some intervention studies[49] indicated that improved combustion conditions by replacement of old woodstoves resulted in lower particle emission levels and consequently lower frequency of irritant symptoms, cold bronchitis, and wheeze in children, there is no supporting evidence from recent studies that improved woodstove technology reduces indoor PM concentrations. However, installation of HEPA filters was found to reduce indoor levels of wood smoke and was related to decreases in systemic inflammatory markers.[41,48]

Although some cell culture studies show that complete wood combustion conditions decrease toxicity of emitted pollutants (primarily particles), more experimental studies in humans are needed to further these findings. A range of physicochemical properties likely influence particle-induced health effects. For example, the deposition and retention of particles in the lung will depend on their physical characteristics and hygroscopicity (how easily water can be absorbed). Particles from complete combustion have greater ability to absorb water, making them less likely to deposit in the lungs. This may influence the magnitude of PM induced toxicity and resulting health outcomes. Complete combustion also decreases PM toxicity expressed as cell survival rate.[35,37,38,48]

The presence of PAHs, acidic or polar substances in emissions from wood combustion are found to have mutagenic effects.[50] Furthermore, several studies provide evidence of carcinogenicity in humans as a result of emissions from wood burning. A review based on seven studies conducted on subjects from North America and Europe, who predominantly used wood as a fuel throughout a lifetime, reported: “an increased risk of lung cancer compared with nonsolid-fuel users”.[51] Furthermore, when controlling for age, smoking, and education, results confirmed an association between wood use and lung cancer among women, likely due to their time spent at home and cooking. A 2010 monograph from the International Agency for Research on Cancer (IARC) classified wood smoke emissions as a group 2A carcinogen (“probably carcinogenic to humans”).[52]

In addition to combustion conditions and physicochemical characteristics of emitted pollutants, the proximity of emission sources and magnitude of emissions are of great importance for exposure scenarios and subsequent health effects. For example, despite less use, more people are being exposed to emissions from wood burning in cities than the lower population rural areas.[53]

With respect to evaluation of wood smoke exposure for toxicological and epidemiological studies, reliable *biomarkers of exposure* are needed, due to variations in exposure-biomarker response relationship for different types of biomass (softwood vs hardwood species burned), different combustion conditions, and inter-individual variation in metabolic rates.

Advanced Wood Combustion Systems (AWC)

The US Environmental Protection Agency (EPA) recently announced that biomass plant emissions will be excluded from regulation for the next three years as more evidence is needed on biomass-related emission characteristics and impacts. The rationale for this decision was to allow for new economic expansion through job creation, investments in biomass plant development, as well as mitigation of greenhouse gas emissions and forest fire prevention. However this decision has led to controversy, given the potential for health impacts related to these emissions.[7]

In studies assessing district heating systems coupled with CHP plants,[54,55] impacts of emissions of NOx and similar (non-CO_2) pollutants should be considered at an urban scale. In the same way, real benefits of distributed electricity generation systems (DG) should be questioned with respect to resulting local air quality. Different exposures to airborne pollutants emitted from such systems may be a result of their location in cities whereas conventional centralized systems are located away from populated areas.[22,54] Emissions from stacks, which can be concentrated or diluted in the local atmosphere depending on meteorological conditions, can impact neighbouring residents.[45] Therefore, it is important to evaluate exposure and not only emissions, in order to assess health effects of newly developed bioenergy systems. Using intake fraction (iF) as a metric for exposure has proven useful in other studies evaluating woodsmoke exposures.[22] IF is defined as the fraction of emitted mass of a pollutant inhaled by exposed people and is independent of a pollutant emission rate, but will be influenced by an exposure setting. Outdoor pollutant concentrations at a location will depend on proximity of a source, effective emission height, and meteorological conditions.[22] A number of studies used this method to estimate iF for wood smoke particles during winter season[56] or to compare exposure to particles from domestic wood burning and other particle sources.[57]

A summary of findings from a selection of studies referred to in the report is presented in Table 1; providing an overview of recent studies which addressed major biomass technologies along with a summary of characteristics and selected impacts.

Table 1. An overview of biomass conversion technologies characteristics, emissions, and selected impacts

Conversion type	Characteristics and emissions	Impacts	References
Direct combustion	• Open burning and household burning which results in high emissions of primary and secondary PM (including BC), BC as a component of fine PM, PAHs, CO, formaldehyde, acrolein, PCDDs, free radicals, SOx, NOx, CO_2; • PCDDs especially released in forest fires; • Industrial combustion/Conventional boilers - controlled conditions allowing complete combustion (above stoichiometric air) result in reduced emissions of PM, carbon, and ash. Smaller combustors (refractory-lined boilers) also decrease PM emissions • Co-combustion with other fuels, e.g., coal – biomass: results in a decrease in SOx, NOx,	Climate impacts: • BC absorbs radiation but also reduction in BC drives photochemistry to increase sulphates and offsets the climate change potential Health effects *Combustion conditions:* • As the magnitude of emitted pollutants is associated with combustion conditions, increased emissions from incomplete combustion potentially lead to higher toxicity • Complete combustion results in lower emissions potentially leading to lower toxicity *Exposure scenario* • Conventional industrial emission sources are usually distant from populated areas, but emissions from local	Kreith&Goswami (ed.)[18] Bariet al.(2010)[58] Boman et al. (2011)[25] Buzcu et al. (2006)[59] An Information Guide (2011)[33]

		sources will impact the affected populations, depending on local geography and meteorological conditions	
Advanced wood combustion (AWC) systems **Gasification**	• Overall lower emissions; CHP NOx still higher than with natural gas, PM emissions require engineered controls • Producer gas has a high caloric value • Gasification through decoupling reactions reduces levels of sulphur(in case coal is used) and nitrogen emissions • Co-gasification with coal: reduced CO_2,NOx and SOx, lower content of impurities, such as NH_3 and H_2S in the producer gas	Climate impacts • GHG reduction, lower climate change potential Health effects *Exposure aspect:* • CHP systems located in urban areas which consequently increases the number of people exposed to emissions; • AWC can contribute more to total iF compared to traditional plants, when placed within urban areas	Zhang J. et. al.(2010)[40] Miranda et al. (2010)[41] Genon et al.(2009)[54] McIlveen-Wright (2011)[43] Jonsson&Hillring (2006)[55] Heath et al. (2006)[22] Pa et al. (2011)[45]
Integrated systems (BIGCC)	• CO_2 emissions significantly reduced compared to other integrated systems IGCC (conventional with coal)	Climate impacts •Lower climate change potential Health effects N/A[c]	Corti (2004)[21]

As illustrated in Table 1**,** even within the direct combustion category there is a diversity of biomass combustion options, ranging from the higher emission forest-fires and open burning sources to conventional type of boilers. With controlled conditions, boilers with complete combustion have reduced emissions, particularly of PM. Lower emissions are also observed with AWC systems, especially when gasification and BIGCC are involved. With these latter technologies there is less potential to affect climate change. Little data is available on health effects associated with AWC systems (and none on integrated BIGCC systems).

Concluding Remarks

The evaluation of particular technologies (fuel type, combustion characteristics, and combination of technologies) should be accompanied by evaluation of resulting air quality and health risks of the exposed population.

[c] N/A – not available; none of the studies evaluating health effects from BIGCC are identified in this literature review

In that regard:

- Evidence shows that quantity and chemical composition of airborne pollutants emitted from biomass burning will depend to a large extent on combustion technology and operating conditions; complete combustion (higher than stoichiometric level of oxygen) in advanced biomass systems leads to lower levels of pollutants;

- Biomass feedstock composition plays a role in emissions and subsequent health impacts - industrial bio-wastes have higher levels of sulphur oxide and nitrogen oxide emissions than forest feedstock. Use of forest residues can lead to cleaner conversion with lower pollution levels and higher process efficiency than industrial and municipal bio-wastes.

- The proximity of emission sources and magnitude of emissions are of great importance for exposure scenarios and subsequent health effects. Wood burning in residential areas can lead to a higher fraction of emitted mass of pollutants inhaled by exposed people.

Evidence Gaps

- Several studies indicated that PM composition was shown to be heterogeneous and largely dependent on combustion conditions and feedstock (type of biomass) used. More experimental and epidemiological studies are needed to evaluate PM characteristics and associated toxicity under different conditions of burning biomass.

- Although some cell culture studies show that complete wood combustion conditions decrease the toxicity of emitted pollutants (primarily particles), more experimental studies on humans are needed.

- Studies of health outcomes are usually limited to evaluating acute effects. Long-term exposure data on biomass burning of different biomass combustion methods is needed to evaluate chronic health outcomes, such as cancer and cardiorespiratory health effects.

- There are insufficient data on emissions from co-processing of biomass and fossil fuels, that may result in reduced emissions or emissions with different toxicological characteristics.

- Since AWCs are located in larger communities and the number of AWCs is increasing in Canada, more exposure studies are needed (particularly on new biomass technologies) to further our understanding of exposures and associated health risks.

- More research is needed on effects of operating conditions on emissions from AWC applications, such as small biomass district heating plants.

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References

1. Evans A, Strezov V, Evans TJ. Sustainability considerations for electricity generation from biomass. Renew Sust Energ Rev. 2010;14(5):1419-27.
2. Richter Dd, Jenkins DH, Karakash JT, Knight J, McCreery LR, Nemestothy KP. Wood energy in America. Science. 2009;323(5920):1432 -3.
3. Ries FJ, Marshall JD, Brauer M. Wood energy: The dangers of combustion. Science. 2009;324(5933):1390.
4. Biomass. The American Heritage Dictionary of the English Language. Fourth ed. New York, NY: Houghton Mifflin Company; 2000.
5. Natural Resources Canada. About electricity. Ottawa, ON: Government of Canada; 2009; Available from: http://www.nrcan.gc.ca/energy/sources/electricity/1387.
6. Bradley D. Canada biomass-Bioenergy report Ottawa, ON: Climate Change Solutions; 2006 May. Available from: http://www.bioenergytrade.org/downloads/canadacountryreportmay312006.pdf.
7. Barnard J. EPA gives break to biomass over climate. Seattle Times. 2011 Jan 12. Available from: http://seattletimes.nwsource.com/html/localnews/2013919368_apusbiomassepa1stldwritethru.html.
8. Obernberger T. Combustion and gasification of solid biomass for heat and power production in Eruope - State-of-the-art and relevant future developments (keynote lecture). Proceedings of the 8th European Conference on Industrial Furnaces and Boilers; Vilamoura, Portugal: CENERTEC; 2008. Available from: http://bios-bioenergy.at/uploads/media/Paper-Obernberger-CHP-Overview-2008-03-18.pdf.
9. Energy Technology Network IEA-ETSAP. Biomass for heat and power. Paris Cedex 15, France: International Energy Agency Secretariat; 2010 May. Available from: http://iea-etsap.org/web/E-TechDS/PDF/E05-Biomass%20for%20HP-GS-AD-gct.pdf.
10. Dymond CC, Titus BD, Stinson G, Kurz WA. Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. Forest Ecol Manag. 2010;260(2):181-92.
11. Beintema N, Bisiaux A, (International Institute for Sustainable Development). International conference "The European forest-based sector: Bio-responses to address new climate and energy challenges?" 6-8 November 2008. European Forests Energy Clim Bull. 2008 Nov;157(1).
12. Ralevic P, Layzell DB. An inventory of the bioenergy potential of British Columbia. Kingston, ON: BIOCAP Canada Foundation; 2006 Nov. Available from: http://www.biocap.ca/images/pdfs/BC_Inventory_Final-06Nov15.pdf.
13. Mahmoudi M, Sowlati T, Sokhansanj S. Logistics of supplying biomass from a mountain pine beetle-infested forest to a power plant in British Columbia. Scand J Forest Res. 2009;24:76-86.
14. Schwab O, Maness T, Bull G, Roberts D. Modeling the effect of changing market conditions on mountain pine beetle salvage harvesting and structural changes in the British Columbia forest products industry. Can J Forest Res. 2009;39(10):1806-20.

15. Hall DO, Scrase JI. Will biomass be the environmentally friendly fuel of the future? Biomass Bioenerg. 1998;15(4-5):357-67.
16. Rubio-Maya C, Uche-Marcuello J, Martínez-Gracia A, Bayod-Rújula AA. Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources. Applied Energy. 2011;88(2):449-57.
17. Natural Resources Canada. Bio-pathways project. Advanced conversion technologies. Ottawa, ON: Government of Canada; 2012; Available from: http://cfs.nrcan.gc.ca/pages/329/4.
18. Kreith F, Goswami DY. Handbook of energy efficiency and renewable energy. Boca Raton, FL: CRC Press; 2007.
19. Madlener R, Bachhiesl M. Socio-economic drivers of large urban biomass cogeneration: Sustainable energy supply for Austria's capital Vienna. Energ Policy. 2007;35(2):1075-87.
20. Schuster A, Karellas S, Kakaras E, Spliethoff H. Energetic and economic investigation of Organic Rankine Cycle applications. Appl Therm Eng. 2009;29(8-9):1809-17.
21. Corti A, Lombardi L. Biomass integrated gasification combined cycle with reduced CO2 emissions: Performance analysis and life cycle assessment (LCA). Energy. 2004;29(12-15):2109-24.
22. Heath GA, Granvold PW, Hoats AS, Nazaroff WW. Intake fraction assessment of the air pollutant exposure implications of a shift toward distributed electricity generation. Atmos Environ. 2006;40(37):7164-77.
23. Basu P, Butler J, Leon MA. Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants. Renewable Energy. 2011;36(1):282-8.
24. Granada E, Lareo G, Miguez JL, Moran J, Porteiro J, Ortiz L. Feasibility study of forest residue use as fuel through co-firing with pellet. Biomass Bioenerg. 2006;30(3):238-46.
25. Boman C, Pettersson Er, Westerholm R, Boström D, Nordin A. Stove performance and emission characteristics in residential wood log and pellet combustion, Part 1: Pellet stoves. Energ Fuel. 2011;25:307-14.
26. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, et al. Woodsmoke health effects: A review. Inhal Toxicol. 2007;19(1):67-106.
27. Kehbila AT. Evaluation of primary wood processing residues for bioenergy in British Columbia [Master of Science thesis]. Vancouver, BC: University of British Columbia; 2010. Available from: https://circle.ubc.ca/handle/2429/27915.
28. Gustafson P, Barregard L, Strandberg B, S?llsten G. The impact of domestic wood burning on personal, indoor and outdoor levels of 1,3-butadiene, benzene, formaldehyde and acetaldehyde. J Environ Monit. 2007;9(1):23.
29. U.S. Environmental Protection Agency. Consumers - Energy efficiency and wood-burning stoves and fireplaces. Washington, DC: EPA; 2011; Available from: http://www.epa.gov/burnwise/energyefficiency.html.
30. Luckow P, Wise MA, Dooley JJ, Kim SH. Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO2 concentration limit scenarios. Int J Greenh Gas Con. 2010;4(5):865-77.
31. Anenberg SC, Talgo K, Arunachalam S, Dolwick P, Jang C, West JJ. Impacts of global, regional, and sectoral black carbon emission reductions on surface air quality and human mortality. Atmos Chem Phys. 2011;11(14):7253-67.
32. Unger N, Bond TC, Wang JS, Koch DM, Menon S, Shindell DT, et al. Attribution of climate forcing to economic sectors. Proc Natl Acad Sci U S A. 2010 Feb 3, 2010;107(8):3382-7.
33. An information guide to pursuing biomass energy opportunities and technologies in British Columbia for First Nations, small communities, municipalities and industry. Kingston, ON: BIOCAP Canada Foundation, prepared for BC Ministry of Energy, Mines and Petroleum Resources; BC Ministry of Forests and Range; 2008 Feb. Available from: http://www.energyplan.gov.bc.ca/bioenergy/PDF/BioenergyInfoGuide.pdf.

34. Hueglin C, Gaegauf C, Künzel S, Burtscher H. Characterization of wood combustion particles:Morphology, mobility, and photoelectric activity. Environ Sci Tech. 1997;31(12):3439-47.
35. Kocbach Bølling A, Pagels J, Yttri KE, Barregard L, Sallsten G, Schwarze PE, et al. Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties. Part Fibre Toxicol. 2009;6:29-.
36. Boman C, Nordin A, Boström D, Öhman M. Characterization of inorganic particulate matter from residential combustion of pelletized biomass fuels. Energ Fuel. 2004;18:338-48.
37. Löndahl J, Swietlicki E, Pagels J, Massling A, Boman C, Rissler J, et al. Respiratory tract deposition of particles from biomass combustion. J Phys Conf Ser. 2009;151:012066.
38. Londahl J, Pagels J, Boman C, Swietlicki E, Massling A, Rissler J, et al. Deposition of biomass combustion aerosol particles in the human respiratory tract. Inhal Toxicol. 2008 Aug;20(10):923-33.
39. Boman BC, Forsberg AB, Jarvholm BG. Adverse health effects from ambient air pollution in relation to residential wood combustion in modern society. Scand J Work Environ Health. 2003 Aug;29(4):251-60.
40. Zhang J, Wang Y, Dong L, Gao S, Xu G. Decoupling gasification: Approach principle and technology justification. Energ Fuel. 2010;24(12):6223-32.
41. Miranda T, Roman S, Arranz JI, Rojas S, Gonzalez JF, Montero I. Emissions from thermal degradation of pellets with different contents of olive waste and forest residues. Fuel Process Technol. 2010;91(11):1459-63.
42. Sethuraman S, Huynh CV, Kong S-C. Producer gas composition and NOx emissions from a pilot-scale biomass gasification and combustion system using feedstock with controlled nitrogen content. Energ Fuel. 2011;25(2):813-22.
43. McIlveen-Wright DR, Huang Y, Rezvani S, Mondol JD, Redpath D, Anderson M, et al. A techno-economic assessment of the reduction of carbon dioxide emissions through the use of biomass co-combustion. Fuel. 2011;90(1):11-8.
44. Skodras G, Grammelis P, Kakaras E, Sakellaropoulos GP. Evaluation of the environmental impact of waste wood co-utilisation for energy production. Energy. 2004;29(12-15):2181-93.
45. Pa A, Bi XT, Sokhansanj S. A life cycle evaluation of wood pellet gasification for district heating in British Columbia. Bioresour Technol. 2011;102(10):6167-77.
46. Noonan CW, Balmes JR. Biomass smoke exposures: Health outcomes measures and study design. Inhal Toxicol. 2010;22(2):108-12.
47. Lillieblad L, Szpila A, Strand M, Pagels J, Rupar-Gadd K, Gudmundsson A, et al. Boiler operation influence on the emissions of submicrometer-sized particles and polycyclic aromatic hydrocarbons from biomass-fired grate boilers. Energ Fuel. 2004;18(2):410-7.
48. Sehlstedt M, Dove R, Boman C, Pagels J, Swietlicki E, Löndahl J, et al. Antioxidant airway responses following experimental exposure to wood smoke in man. Part Fibre Toxicol. 2010;7:21.
49. Noonan CW, Ward TJ. Environmental tobacco smoke, woodstove heating and risk of asthma symptoms. J Asthma. 2007;44(9):735-8.
50. Straif K, Baan R, Grosse Y, Secretan B, El Ghissassi F, Cogliano V. Carcinogenicity of household solid fuel combustion and of high-temperature frying. Lancet Oncol. 2006;7(12):977-8.
51. Hosgood HD, Boffetta P, Greenland S, Lee Y-CA, McLaughlin J, Seow A, et al. In-home coal and wood use and lung cancer risk: A pooled analysis of the International Lung Cancer Consortium. Environ Health Perspect. 2010;118:1743-7.
52. International Agency for Research on Cancer (IARC). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Household use of solid fuels and high temperature frying. Geneva, Switzerland: World Health Organization; 2010. Available from: http://monographs.iarc.fr/ENG/Monographs/vol95/mono95.pdf.

53. Summary findings from the Border Air Quality Study. Vancouver, BC: University of British Columbia; Study was funded by Health Canada; 2008 Mar. Available from: http://baqs.spph.ubc.ca/sites/envhealth.drupalprod.webi.it.ubc.ca/files/uploads/ubcbaqs/BAQS_Summary_Mar08%20copy.pdf.
54. Genon G, Torchio MF, Poggio A, Poggio M. Energy and environmental assessment of small district heating systems: Global and local effects in two case-studies. Energ Convers Manage. 2009;50(3):522-9.
55. Jonsson A, Hillring B. Planning for increased bioenergy use—Evaluating the impact on local air quality. Biomass Bioenerg. 2006;30(6):543-54.
56. Ries FJ, Marshall JD, Brauer M. Intake fraction of urban wood smoke. Environ Sci Technol. 2009;43(13):4701-6.
57. Tainio M, Karvosenoja N, Porvari PR, A, Tuomisto JT, Johansson M, Kukkonen J, et al. A simple concept for for gis-based estimation of population exposure to primary fine particles from vehicular traffic and domestic wood combustion. Boreal Environ Res. 2009;14:850-60.
58. Bari MA, Baumbach G, Kuch B, Scheffknecht G. Particle-phase concentrations of polycyclic aromatic hydrocarbons in ambient air of rural residential areas in southern Germany. Air Qual Atmos Health. 2010;3(2):103-16.
59. Buzcu B, Yue ZW, Fraser MP, Nopmongcol U, Allen DT. Secondary particle formation and evidence of heterogeneous chemistry during a wood smoke episode in Texas. J Geophys Res. 2006;111(D10):D10S3.

APPENDIX A: Literature Search Methodology

Online Indexes and Databases

Literature search was based on electronic resources available from the University of British Columbia library. The following three databases were searched to retrieve literature for this paper:

Web of Science: An on-line database with multidisciplinary content which consists of: Science Citation Index Expanded, Social Sciences Citation Index, Arts and Humanities Citation Index, Conference Proceedings Citation Index- Science http://apps.isiknowledge.com; http://resources.library.ubc.ca/277

PubMed Central (PMC)*:* An on-line database containing articles in medicine and health sciences subject areas. It is produced by the National Center for Biotechnology Information (NCBI) at the U.S. National Library of Medicine (NLM) http://www.ncbi.nlm.nih.gov/pmc/; http://resources.library.ubc.ca/571

Google Scholar (GS*)*: An on-line un-restricted database containing a broad range of scholarly literature including peer-reviewed papers, theses, books, preprints, abstracts, technical reports. http://scholar.google.ca/; http://resources.library.ubc.ca/943

Search Terms and Inclusion Criteria

Text searches were conducted using search terms from a matrix organized as search concepts (such as, feedstock, emissions, and health) and assigning alternative terms for each concept, for example: for feedstock – wood, biomass, forest residues. Search terms were then combined using Boolean logic (AND, OR) to reduce the search results to those considered to be most relevant to the topic. In addition, “wildcards” were used where appropriate in order to retrieve variants on terms (e.g., wood*). The selection of retrieved material was restricted to those published since year 2000 and English language only.

Most literature sources used were retrieved from the mentioned on-line data bases and resulted in:

a) 403 papers from Web of Science; the number of papers retrieved varied widely depending on the combination of search terms. For example, when searching for *forest residues AND emissions AND health** only 5 papers were retrieved, while when searching for *energy systems AND emissions AND health** a total of 148 papers were retrieved;

b) 249 papers retrieved from PMC but 165 full text papers; and

c) 400 papers from GS using search terms which retrieved fewer papers in other data bases; also, particular journals such as Renewable Energy and Biomass and Bioenergy were searched since 2000 in order to narrow down the search. Abstracts, and in some cases introduction and/or conclusion sections of all retrieved papers, were read to help narrow the number of papers for consideration, based on their relevance to the paper objectives and inclusion criteria.

Additional grey literature was searched by accessing US EPA, Natural Resources Canada (NRC), BIOCAP Canada, BC Bioenergy Network as well as recent media releases. Some publications and articles were recommended by reviewers of the draft report.

Reference software and literature storage

Bibliographic data for the obtained electronic literature was saved using online citation management software ZOTERO (http://www.zotero.org/) which enables access from other computers by its "sync" function. Additionally, electronic copies of cited literature were stored on the hard drive of author's computer.

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