Transforming Saskatchewan's Electrical Future

PART FOUR

Plugging the Gap: Sustainable Power Options to Complement Wind and Solar

By Mark Bigland-Pritchard

CCPA
CANADIAN CENTRE for POLICY ALTERNATIVES
CENTRE CANADIEN de POLITIQUES ALTERNATIVES

Saskatchewan Office
Suite G — 2835 13th Avenue
Regina, SK S4T 1N6

www.policyalternatives.ca

Transforming Saskatchewan's Electrical Future

PART FOUR

Plugging the Gap:
Sustainable Power Options to Complement Wind and Solar

By Mark Bigland-Pritchard

June 2011

This paper is written as part of an ongoing project, Green Energy Project Saskatchewan. GEPS is a civil society group, established to develop a plan for the conversion of Saskatchewan's electricity grid to sustainable renewable options by the earliest possible date. Stemming both from concern for the welfare of the human species and from a respect for the earth and all of its natural systems, we seek the attainment of sustainability, as defined by the UN-sponsored Brundtland report in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Basic principles of compassion and justice demand that we move rapidly to phase out fossil fuel usage and therefore eliminate our largest contribution to global climate change. We owe this to all the potential victims of climate change, locally, nationally and globally, in our generation and in generations to come. We therefore seek options for energy provision which are based on the following principles:

- Efficient use of resources — achieving desired results with as little energy consumption as is realistically possible.
- Use of renewable options — i.e. the energy sources which will endure for as long as possible.
- Technical viability — both innovative and traditional choices, designed and assessed according to the best available scientific and technological methods available.
- Recognition and respect for the rights of indigenous people at home and low-income people worldwide in the choice of technologies and the way in which they are implemented.
- Minimization of negative environmental impacts and respect for ecosystems.
- Optimization of opportunities for local social and economic development.

More information on GEPS and sustainable energy practices can be found at our website: *http://greenenergysask.ca*

About the Author

Mark Bigland-Pritchard operates as a consultant in energy, environmental assessment, green building and architectural physics through his company, Low Energy Design Ltd. His background includes two engineering degrees, a PhD on energy performance and moisture risk in strawbale construction, several years of teaching energy studies at the Open University and the University of Sheffield (in Britain), and a diverse range of consultancy work in the public, private and voluntary sectors, spread over two decades and three continents. He is a former director of the Saskatchewan chapter of the Canada Green Building Council.

Printed copies: $10.00. Download free from the CCPA website.

ISBN 978-1-926888-42-2

Transforming Saskatchewan's Electrical Future

Plugging the Gap: Sustainable Power Options to Complement Wind and Solar

This paper is part four of a five-part series on the potential for a sustainable electricity grid in Saskatchewan. Previous papers in this series have addressed the need for a radical change to the philosophy behind Saskatchewan's electricity generation,[1] the potential for efficiency and conservation savings,[2] and the role which may be taken by variable renewables (wind and photovoltaics).[3]

In my discussion of wind and photovoltaics in part three, I noted the need for dispatchable (i.e. quick-response) power sources to partner with the variable renewables (wind and solar) to ensure power security for customers. In the short term, this role may be taken by "natural" (i.e. fossil) gas and by existing hydroelectric facilities. However, there will be a requirement to build capacity, as dispatchables become more important in a renewables-based system than they have been in the existing system founded on coal-fired "baseload". Additionally, in order to reach the greenhouse gas emissions targets necessary for maintenance of sustainable human civilization worldwide, use of natural gas will need to be phased out (though, on account of its lower emissions per kWh, less urgently than coal).

One purpose of this paper, therefore, is to investigate some of the options for power which is (i) dispatchable and (ii) sustainable into the foreseeable future. The full range of potentially realistic options are discussed on page 4 onwards.

There is a further task which is necessary to any consideration of renewable energy in Saskatchewan. A review of options should start with those characterized by plentiful resources. Aside from wind and solar, the most obvious renewable energy resource in the province is biomass — energy from renewable sources of biological origin. In principle, a low population density permits consideration of a much greater penetration of biomass options into the energy market than would be possible in most other developed economies. However, there are constraints on biomass production which do not apply in other areas — for example, the requirements of agriculture and of a diverse ecosystem.

Therefore this paper's second, overlapping, purpose is to consider the possible role of both dispatchable and non-dispatchable biomass energy options. This will be addressed in detail on page 8.

Sustainable Options for Dispatchable Power

There is only a limited number of potentially viable technologies which either provide dispatchable generating capacity or else render variable sources dispatchable. These are:

i) Various fuels of biological origin, in gaseous form. These are discussed in detail on pages 8-13.

ii) Dammed (and, to a limited extent, run-of-river) hydroelectric plants.

iii) Storage, either integrated with wind or photovoltaic facilities, or else as a separate facility on the grid: this is not a dispatchable source in itself, but can render wind and photovoltaic dispatchable.

iv) Concentrating solar thermal technology.

v) Hybrid systems.

Options (ii) to (v) are treated in reverse order in the sections which follow.

Concentrating Solar Thermal and Hybrid Systems

In a concentrating solar thermal (CST) plant, mirrors are used to focus the sun's rays into a target area. A number of options exist, depending on the geometry of the collector system used.[4]

With one exception (a research installation in Jülich, Germany[5] — at about 51 deg north), all currently functioning CST power stations are at a lower latitude than Saskatchewan, and generally in areas with markedly higher annual insolation (total solar radiation).[6] Existing North American facilities are all in the southwestern United States or Hawaii; the majority of European CST schemes are in Spain, supported by a generous feed-in tariff. A sunny climate is clearly important to the success of this type of project — actually more so than for other solar technologies because cloudy skies make it difficult or impossible to reach the "target" temperature necessary to achieve any electrical generation at all (whereas for photovoltaics the output is merely reduced in diffuse radiation). Latitude also makes a difference — at high latitudes, the ability of the facility to generate power in winter is limited because of short daylight hours. (The Jülich solar tower produces solar power for only about two-thirds of the year.) While it is possible to reduce the temperature required for power production by making use of Organic Rankine Cycle (ORC) technology or Stirling cycles instead of a conventional steam turbine, and hence increase the number of days of operation per year, this approach reduces overall efficiency on high-production days.

Hence it is reasonable to assume that this technology's time has not yet come in Saskatchewan. However, it remains a possible future option.

High-temperature thermal storage can enable power production to continue for hours or in some cases days after the end of a good sunny period: this gives the technology some degree of dispatchability. It is also possible to develop a hybrid system, in which auxiliary heating (for example, by bio- or fossil gas) is used to ensure continuous operation.

Another technology with potential for use in hybrid systems is deep geothermal heat extraction.[7] Again, temperatures in Saskatchewan's deep geothermal aquifers are not adequate for electricity generation: if not used solely for space heating, this resource could be used for preheat for conventional thermal turbines.

Storage

Energy storage on a scale relevant to a provincial grid is not impossible. While it can add to the financial cost of electricity grid development and maintenance, the resulting per-kWh price rise for the customer does not need to be prohibitively expensive, as money spent on storage can be at least partially offset by savings on capacity and on operation of "peaking" units.[8] However, it is likely to imply significant environmental costs — for example, in mining and refining of metals for batteries, or in landscape and water flow alteration for pumped storage. Hence it is not recommended here as the first course of action in firming up variable sources, but can still play an important role and will certainly be needed during the later phases of the transition to sustainability. Options suitable for grid-scale electricity supply management include the following:

Pumped Hydroelectric Storage: Water is pumped uphill into a reservoir during times when power production exceeds demand; it is then released through a turbine generator into a lower reservoir at times when demand exceeds production.[9] This option is common in mountainous jurisdictions,[10] but in Saskatchewan a more appropriate location could be a decommissioned mine, with the upper reservoir on the surface and the lower reservoir underground.

Redox Flow Batteries: A flow battery (or flow cell) is similar to a rechargeable battery — energy is stored by converting from electrical to chemical energy, and released by reversing the process.[11] However, in a flow battery, the chemical changes occur within tanks of dissolved metal salts rather than at metal electrodes: this means that the electrical capacity of the battery may be increased merely by increasing the volume of fluid in the tanks (as opposed to adding more batteries), and so significant economies of scale are possible. (Flow batteries are also similar in design to fuel cells in that the two electrolyte tanks are separated by a proton exchange membrane.) A promising option is the redox vanadium flow cell, which makes use of the ability of vanadium to exist in four different oxidation states.[12] It was first developed for an experimental project in Australia in the 1980s, and has now been commercialized in Austria, Ireland, China, Thailand and the United States.

Advanced Rechargeable Batteries: The options currently viewed as most promising are lithium-ion cells (used on a smaller scale in laptop computers, cellphones and some hybrid vehicles) and sodium-sulphur cells[13] (which use molten sodium metal at a temperature of 300 to 350°C, and so are suitable only for large-scale operations). One promising option (in that it significantly reduces costs to the utility company) is to make use of the large battery assemblies in plug-in hybrid vehicles to store and release grid power when not in use for transportation.

Compressed Air Energy Storage (CAES): Air is compressed in underground caverns and then released as needed though a gas turbine. In most existing schemes, natural gas is used to supplement output: hence this is not necessarily a fully renewable option.[14]

Flywheels: Surplus electricity is used to power a motor/generator, which drives a rotating cylinder enclosed within a low pressure or a vacuum environment. The motor driving the flywheel acts as a generator when power is needed. This option is of use only for short-term power smoothing, not for long-term storage.[15]

Supercapacitors: Two plates, separated by an electrolyte, are used to store electric charges of equal and opposite magnitude. During discharge, the built up charges on the plates create a current.[16] Supercapacitors are best suited to applications of short duration.

Hydrogen Storage: Water is converted, by means of electrolysis, into hydrogen and oxygen. The hydrogen is stored in compressed form, and is used to generate power when needed using a fuel cell or a reciprocating engine. Despite much publicity about "the hydrogen economy", this is probably the least promising storage option because of low conversion efficiencies and the complex logistics of setting up electrolysis facilities and distribution systems.[17]

Hydroelectricity

Hydro plants may be categorized as one of two types. In ***dammed*** hydro plants, it is possible to control water levels in a reservoir (or sometimes a natural lake) above the turbine, and hence also the flowrate through the turbine. In ***run-of-river*** plants, there is minimal modification to natural river flow. The latter clearly cause less disruption to the local ecology (provided they are subjected to proper assessment at the application stage), and so also have a lesser impact on indigenous people in the north, whose way of life depends on reliable availability of fish, beaver, moose, etc. Because of its impact on both human societies and ecological systems, new dammed hydro cannot generally be regarded as sustainable (unless constructed in less sensitive locations, and with the full, active, willing and informed involvement of local indigenous people after a process of true consultation involving the whole community). While there is some potential for new run-of-river plants in Saskatchewan, it is highly unlikely that new dammed hydro could be part of our plan.

Cuileig run-of-river hydro plant in Scotland.

Unfortunately, however, hydro is considerably more dispatchable when it makes use of the large energy storage facility created by a dam. Run-of-river plants can store only limited amounts of water, and only for 48 hours[18] — useful for smoothing out small daily fluctuations in wind power but not large-scale variability. Hence the possible contribution of existing and new Saskatchewan-generated hydroelectricity is real but limited. (Such projects should, however, be actively pursued — provided that, wherever they lie in traditional First Nations and Métis hunting, trapping and fishing territory, those communities are fully consulted, fully in agreement and full partners in the scheme. SaskPower figures suggest that somewhere between 150 and 200 MW of new generating capacity could be brought online in this way.[19])

A further, and probably more promising, option would be to trade electricity with neighbouring provinces where the hydro capacity already exists. One of the major ways in which Denmark stabilises its electricity supply is to sell excess wind power to Norway and Sweden, and to purchase hydro power from those countries at times of low wind output. Saskatchewan could pursue a similar relationship with Manitoba. Manitoba Hydro — a 97% hydroelectric utility company — generates a substantial surplus of electricity: over the last five years, electricity generated minus losses has exceeded Manitoba's demand by an average of 33%.[20] The surplus is nearly all sold into the USA at present.

With over 80% of Manitoba's hydro coming from the Nelson River and effectively using Lake Winnipeg as a reservoir,[21] it is reasonable to expect that this massive storage facility could cope with a significant proportion of the short-term fluctuations resulting from variations in wind power output. However, it is important to assess the impact on lake shoreline communities in Manitoba, and especially on First Nations and Métis. There has already been substantial disruption to these communities as a result of existing hydro schemes.[22] (The problems encountered have been magnified by other factors: the current effect of climate change in the eastern prairies is to increase spring flood risk; and water is diverted from the Assiniboine River into Lake Winnipeg in order to protect the city of Winnipeg and other parts of southern Manitoba.)

It is relatively easy to estimate the impact of the variability of Saskatchewan wind on Lake Winnipeg. To take a fairly extreme example: if Saskatchewan were to draw power from Manitoba for two full days at a rate of 1000 MW then, all other things being equal, the level of Lake Winnipeg would drop by 1.2 m. Given that Manitoba Hydro is required to maintain lake levels within a 1.2 m range, this level of dependence on imports would not be viable. But drawing the same amount of power from Manitoba for 20 minutes would result in only a 100 mm level change.

The impact of these water level changes should not be disregarded in Saskatchewan's future plans. In 2001, a church-based commission[23] heard testimony about the impact of the Churchill-Nelson Hydroelectric Project, which put the bulk of Manitoba's present generating capacity in place during the 1970s and 1980s. Representatives of about 60 local communities and interests testified. The commission's conclusions include the following paragraph: "The untallied cost of electricity production in northern Manitoba has been two decades of extensive environmental destruction, violation of human rights, and even the loss of life. For Manitoba Hydro, the governments and consumers, the Project is a success, but in northern Manitoba it constitutes an ongoing ecological, social and moral catastrophe. These imbalances must be redressed." The damage has been done, and so First Nations representatives with whom I spoke when researching this paper saw no problem in principle with Saskatchewan purchasing from Manitoba Hydro or using the existing "Project" for power output smoothing. However, it is important that the terms of any interprovincial trading agreement be such as to avoid exacerbating the problems encountered by Manitoba's northern communities. To add to the burden on these communities is neither just nor sustainable. For this reason, it is difficult to justify ethically any agreement which would result in Manitoba adding further hydro capacity to its grid (unless it is developed in a way which is unequivocally acceptable to the local communities), but instead argue for a limited two-way trading arrangement, subject to responsible management of lake levels.

A further consideration is that we would be in competition with Manitoba's US partners — and in particular Minnesota — for the limited energy storage facility described here. An agreement has already been signed — but not ratified — between Manitoba Hydro and Minnesota Power, to "allow Minnesota to essentially use Manitoba as a rechargeable battery by storing energy from wind farms in North Dakota".[24]

To summarize, a stronger interconnection with Manitoba is desirable, but it can offer only a partial contribution towards stabilizing output from renewables, and when put in place it should not be used for extended periods of time. Other measures will be required to adequately handle the (relatively rare) occasions when the whole of southern Saskatchewan is becalmed for days or even hours rather than minutes. Detailed planning of a sustainable Saskatchewan electricity grid must involve consultation not only with Manitoba Hydro but also with impacted First Nations and Métis communities.

At present, interconnections between the Manitoba and Saskatchewan grids exist, to the extent of 150 MW in one direction and 275 MW in the other.[25] For significant electricity trading to occur between the two provinces, the interconnection capacity would need to be expanded, possibly to as much as 1000 MW in both directions. Trade should ideally be two-way, with excess Saskatchewan wind generation sold to

Manitoba. A recently-publicized proposal for a new 100 MW interconnection[26] is a small step in the right direction.

A General Comment

Without storage, it is likely that the energy from variable sources (wind and photovoltaics) will be limited to between 25% and 35% of the total. With storage, this proportion can be higher, but at a cost which escalates rapidly as the variables' contribution increases. Hence probably at least 50%, and maybe 75%, of Saskatchewan's power will need to come from other sources. Even with a concerted programme of demand side management, efficiency measures and conservation, this is likely to mean between 12000 and 18000 GWh per year in the mid-2020s unless expansion of extractive industries is severely curtailed. The maximum average annual contribution to this figure from Saskatchewan hydro power is less than 5000 GWh/yr if subjected to the ethical standards laid out above. The other options considered so far cannot be relied upon to even come close to filling the gap. The bulk of the remaining 7000 to 13000 GWh/yr needs to come from the only remaining serious option, biomass energy.

(Note: The province's total electricity requirements can be reduced in time through further efficiency savings and through transition to a less energy-intensive economic base. However, radical changes to the Saskatchewan economy do not come within the remit of these papers — we need to make the conservative assumption that the types of growth patterns currently envisaged by SaskPower will indeed come to pass.)

An Incomplete Introduction to Biomass Energy

Energy from biomass is a complex subject: there are multiple possible sources, and multiple means of processing the raw material, resulting in a variety of combustible end-products. Depending on whether the final combusted product is solid, liquid or gas, biomass may be used for production of heat, electricity, transport fuel or some mixture of the three. In North America and Brazil (and to a lesser extent in Europe), there has been a focus on automotive fuel (bioethanol, biodiesel, etc.) almost to the exclusion of heat and electricity. This has been a mistake, primarily because the particular biofuels chosen compete for land with food production. There is, however, another reason to consider it a poor choice: it is more energy-efficient, and produces less greenhouse gases, to run an electric car on power from biomass power stations than to fuel a gasoline-engine car with bioethanol.[27] For this reason, and because this series of papers is concerned only with electricity, options for automotive fuels, etc., are not considered here.

The technology for generating electricity from biomass — whether solid or gaseous — is little different from that used in fossil fuel power stations. The fuel is burnt, and the heat used to boil water. The resulting steam is used to drive a steam turbine. In the case of gas-fired stations, the exhaust gases may instead be used to drive a gas turbine (a technology similar to the jet engine). The most energy-efficient option is to combine the two in what is known as combined-cycle gas turbine (CCGT) technology — this can yield process efficiencies of over 50%, compared to 30 to 40% for steam turbines and 20 to 25% for gas turbines alone.

There are two key differences from fossil fuel generation. The first is that every part of the power station needs to be planned to handle the particular fuel being used — in particular, its density, its chemical composition and any corrosive by-products of combustion. Hence it is possible to adapt existing plants designed for fossil fuels, but this is not necessarily a straightforward process.

Secondly, biomass fuels are more bulky than fossil fuels. This restricts the distances which they can sensibly be transported, and hence the size of the power station. In practice, this means that — like wind, photovoltaics and small hydro — biomass power is better suited to community-scale generation as part of a networked "distributed generation" grid than to the current centralized grid. This opens up the possibility of local community ownership and management.

All thermal power stations produce waste heat — partly because the second law of thermodynamics sets a limit on the maximum theoretical efficiency, and partly because of unavoidable losses in the system. A well-planned system built for efficiency will seek to find a use for this waste heat, typically for space and water heating. This approach, which is widespread in much of northern Europe, is known as combined heat and power (CHP) or cogeneration. The best CHP projects find a method of using the heat year-round in buildings with a high usage of hot water (hospitals, leisure centres, hotels, some types of light industry), but community district heating systems can also be worthy of consideration.

Hopper for dropping corn husks into methane digester – Germany.

Biomass possibilities in Saskatchewan are summarized in figure 1.

Possible Sources and Processes

Possible sources include forestry residue, forestry plantations, agricultural crop residue, energy crops, municipal and household organic "waste", animal dung, and cultivated algae. (The suitability of each of these sources will be assessed later in this paper.)

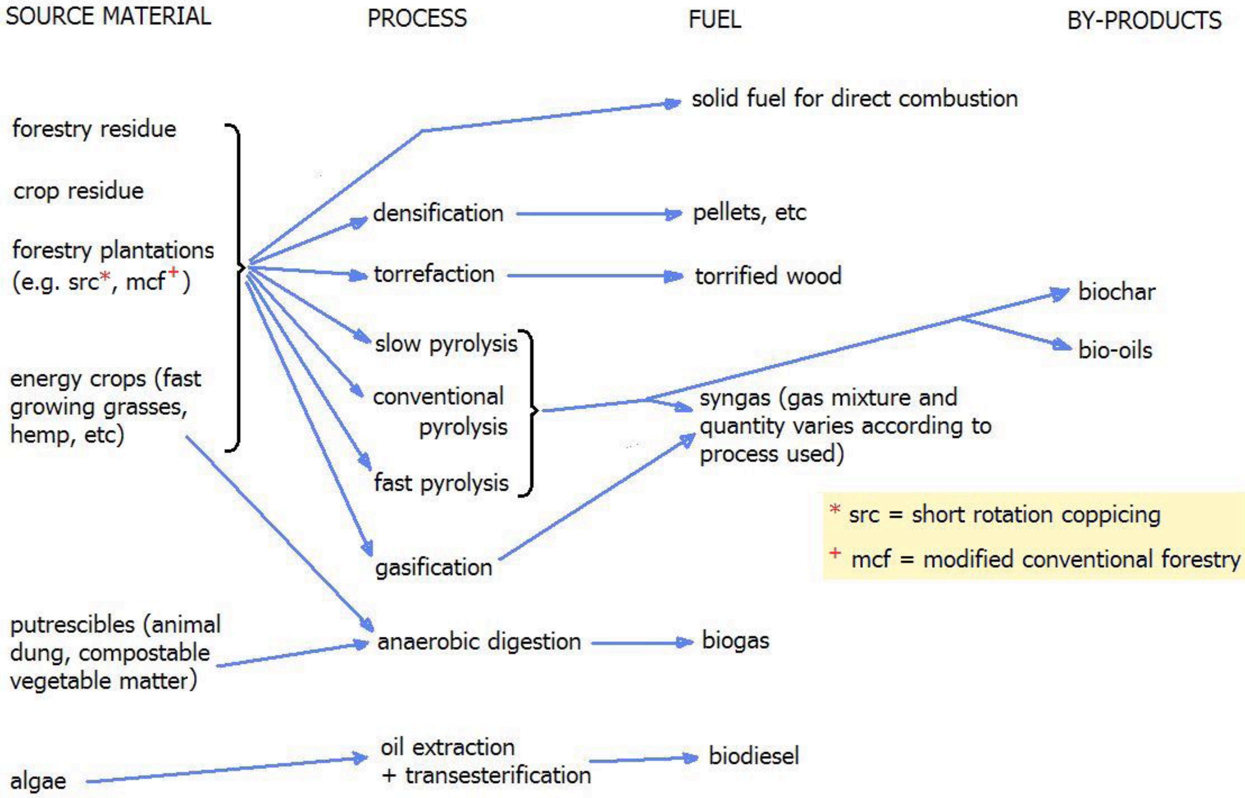
The processes listed in figure 1 require some explanation:

Direct Combustion: The organic matter in the raw or processed fuel is burnt completely (possibly leaving behind ash but not charcoal, tar or other residues).

Densification: Any process by which the density of a solid organic fuel may be increased. For example, wood pellets are formed by extruding sawdust under pressure. They are thus of a standard size and of a uniform density, enabling wood boilers to be readily optimized for their use. They also have a higher energy density (i.e. kWh released per unit volume combusted) than most biomass solids, reducing bulk transport requirements.

Gasification: Heating of organic materials with limited oxygen or air, at temperatures above

Figure 1: Sources and Processes for Production of Biomass Fuels



about 800°C. A variety of gasifiers exist, with a wide range of operating temperatures and pressures, and many (but not all) adding steam to the mix. The product is synthesis gas (or producer gas), a mixture consisting mostly of carbon monoxide and hydrogen.

Pyrolysis: Heating of organic materials with zero (or very little) oxygen or air, so that they decompose. The products typically include char (solid, mostly carbon), "bio-oils" and combustible gases — proportions vary depending on the temperature and pressure.

Fast Pyrolysis: Pyrolysis at temperatures above 450°C, sometimes under pressure. If it is achieved by very rapidly increasing the temperature of the raw material and discharging the products rapidly, it is known as flash pyrolysis. Temperatures of 450 to 550°C optimize the liquid yield; higher temperatures optimize the gas yield.

Conventional Pyrolysis: Pyrolysis at between about 400 and 450°C, at atmospheric pressure.

Slow Pyrolysis: Pyrolysis at temperatures below about 400°C, at atmospheric pressure.

Torrefaction: A type of very low-temperature, very slow pyrolysis — organic materials are "roasted" at temperatures of 200 to 300°C in oxygen-deprived conditions. The result is a densified and water-resistant solid product, and sometimes also a gas.[28]

In general, in pyrolysis processes, more char is obtained with lower temperatures and longer residence times. As the reaction temperature increases, first volatiles and gases and then bio-oils begin to increase in proportions. At higher temperatures still (over 550°C), bio-oils decompose, leaving mostly volatiles.

Anaerobic Digestion: Bacterial action at temperatures in the range from 30°C to 45°C (depending on the bacterial culture used) in the absence of air breaks down organic material, giving off a combustible mixture of gases ("biogas") of which the main component is methane.

Non-Dispatchable Biomass

The greater dispatchability of gaseous fuels, together with their potential for greater electrical conversion efficiency, clearly favours power stations run off synthesis gas, pyrolysis gas or biogas. However, there is one factor which favours solid fuels, and torrefaction in particular — Saskatchewan has both coal-fired plants and expertise in handling solid fuel. There is therefore an argument for maintaining some of the existing coal-fired capacity — possibly Shand power station, which is not due for retirement until 2038 — but converting it to handle torrefied biomass. This would save some existing jobs, and preserve skills which may be needed for the future.

Dispatchable biomass should, however, be the priority. Decisions as to whether to proceed with power from torrefied wood should be dependent on the total size of the sustainably-accessible biomass resource: as will become clear, this is uncertain at present.

Making Sustainable Choices for Biomass

Energy sustainability should not be pursued at the expense of global food security (by taking land unnecessarily out of food production) or ecological sustainability (by replacing native forests or other key habitats). Furthermore, some biomass options necessitate significant fossil fuel inputs or damage existing carbon sinks, either directly or indirectly. I therefore propose a set of ethical criteria by which any given biomass energy proposal may be assessed. To be viewed as sustainable, the full life cycle of biomass schemes should be considered, and they should comply with the following conditions:

1. **There should be a large life cycle energy return on investment (EROI).** EROI is the ratio of the usable energy generated to the energy input required to drive the process: hence an EROI of one represents zero net gain. Another way of expressing this criterion is that the net energy output (i.e. usable energy generated minus energy input required) should be large and positive. There is academic dispute as to whether any of the currently commercialized biofuels-for-transport options has an EROI greater than one.[29] However, neither side of the argument can legitimately generalize its findings to also include all biomass-for-electricity.
2. Likewise, **there should be substantial net reductions in greenhouse gas emissions**, taking all greenhouse gases into account, and calculated using a full life cycle analysis.
3. **The opportunity for dishonest carbon accounting should be minimized.** Biomass schemes internationally often depend on carbon trading ("offsets") for their financial support. The UN's official carbon offsetting scheme, the Clean Development Mechanism, has been widely abused;[30,31] opportunities for similar deceit exist in all trading schemes.
4. **First Nations livelihood and traditional ways of life should be protected**, treaty obligations observed, and genuine consultation carried out (involving the whole community). Likewise, **policies should not be pursued which threaten the livelihood of family farms**.
5. **There should be no net reduction in food production** as a result of biomass schemes (unless already required for vital protection of the local ecology).
6. **There should be no added threat to important wildlife habitats or to biodiversity**, whether directly or indirectly.

7. **There should be no export of the natural means of ensuring soil fertility out of Saskatchewan.** This includes net loss of organic carbon (or its equivalent) from soils.
8. Likewise, **Saskatchewan should not benefit from the loss of the natural means of ensuring soil fertility in other jurisdictions**.
9. The process should be designed such that **nutrients removed from the natural cycle by harvesting biomass are returned to the soil**.

Using these criteria, certain options may be ruled out immediately, and others accepted only for a limited range of applications:

- The artificial nutrient requirements of algae production are, at present, sufficiently energy-intensive to give this technology an EROI of less than one.[32]
- In the vast majority of locations, energy crops and biomass forestry plantations would be diverting land from food production. There are, however, exceptions. In the right conditions, it could be appropriate to proceed with small-scale short rotation coppicing (src) schemes.* These are common in much of Europe, and often double as energy production and agricultural wildlife refuge.[33,34] Research is underway at the Saskatchewan Research Council into use of similar plantations to assist in municipal sewage disposal for towns and villages in the province.[35]
- Much putrescible domestic waste would be better composted and used to enhance urban soil fertility than subjected to any sort of combustion, pyrolysis or gasification process.
- Replacing old-growth forests with faster-growing crops is not only ecologically questionable but leaves a carbon debt which may not be repaid for decades.[36]
- Large-scale anaerobic digestion (AD) requires easy collection of large quantities of putrescible material from a relatively small area — this has proved non-viable for free-roaming cattle even in some locations in England and Wales, where field sizes are much smaller. Hence AD is usually dependent on highly intensive methods of livestock rearing which concentrate nitrogen-rich manure and hence result in high emissions of the greenhouse gas nitrous oxide (N_2O). While most research indicates that AD substantially reduces total greenhouse gas emissions from these schemes (though usually slightly increasing N_2O emissions),[37,38,39,40,41,42] a better climate solution (and a more sustainable solution generally) would be to avoid the most intensive livestock rearing methods altogether.

Which Choices Can Make a Serious Contribution?

The options which appear best able to meet the criteria above are those in which "by-products" of existing activities are used, with only small contributions possible from certain types of purpose-grown vegetation:

*Coppicing is a centuries-old technique, which involves harvesting the growth (i.e. cutting just above the roots) at an interval of several years and allowing the tree to grow back. In short rotation coppicing, species are chosen for rapid growth (in Europe, typically willow or poplar) and conditions optimized to allow a short (two to five year) cycle.

Forestry Residue: This consists of logging slash, sawdust and shavings, bark, other mill waste, and woodland debris. Annual operations result in residues with an energy content of about 1400 GWh. Applying a typical value range for the efficiency of thermal power stations, this could supply up to 500 GWh of electrical energy per year. In addition, stockpiles amounting to a total of about 11000 GWh exist in various locations in the north of the province.

Crop Residue: Substantial quantities of cereal and flax straw, and canola stalks, are produced each year in Saskatchewan. Some cereal straw is used for cattle feed and bedding and for sundry other purposes; of the 16 to 17 million tonnes which remain,[43] the majority can (and mostly does) serve a useful purpose in soil protection (maintaining carbon and organic matter), but about two million tonnes could be available for bioenergy, yielding about 9000 GWh/yr if directly combusted.[44] Applying a typical value range for the efficiency of thermal power stations, this could supply between 2500 and 3000 GWh of electrical energy per year.

Short Rotation Coppice (src) in areas where agricultural forestry can serve an additional purpose — such as enhancing biodiversity, providing cover for game birds, or providing purification services to sewage lagoons. A reasonable estimate for electrical power output from this source in Saskatchewan is about 4 MWh/ha, equivalent to about 0.25 GWh per fully-forested quarter-section.

Modified Conventional Forestry (mcf): In this system, pioneered in Sweden, coniferous trees are planted at relatively high density and thinned after a few years, yielding an early harvest of chipped wood. This approach can only at present be considered suitable for reafforestation projects in the north. There is no obvious reason why schemes of this nature cannot satisfy other sustainability tests such as the principles and criteria of the Forestry Stewardship Council (FSC).[45]

Anaerobic Digestion: Agricultural schemes should use a mixture of crop residue and animal manure. They are, however, limited in scope by the sustainability criteria indicated above. There is also some potential for AD plants at municipal sewage works (this is common in Europe)[46] and also at some large food processing facilities.[47]

Together, these last three options could add maybe another 500 GWh of electrical power per year. This gives a total resource size, after conversion to electricity, of about 3500 or 4000 GWh/year, or a capacity of about 600 MW if used at a capacity factor of 65%. This amounts to a mere 15% of projected electricity demand for 2030. If pyrolytic incineration of urban refuse were to be added to the list, it may be possible to raise that figure to 20%. Biomass options, as currently conceived, will not completely fill the gap in power supply identified above.

There is one biomass-based methodology, currently emerging from research and development, which may be able to dramatically increase this figure — that of pyrolysis with return of biochar to the land. This is discussed in more detail in the section which follows.

Biomass, Carbon Sequestration and Biochar

All of the biomass options chosen above, if well-planned and -designed, have a low carbon footprint. While some fossil energy is used in harvesting and transporting the fuel, constructing the power station, etc., the core processes — crop growth and combustion — are in principle carbon neutral when taken together. The carbon taken from the atmosphere as the crop grows balances out the production of carbon dioxide when it is burnt.

In principle, however, biomass-fuelled electricity could do better than this. It could be carbon negative. To address the current climate crisis adequately, it will be necessary not just to stabilize atmospheric levels of carbon dioxide but ultimately (and as soon as possible) to reduce them. Leading climate scientist Jim Hansen argues convincingly for a reduction of atmospheric carbon dioxide from its current concentration of over 390 parts per million (ppm) to 350 ppm or less.[48] Higher concentrations for extended periods of time would bring the earth's climate system to "tipping points" beyond which human civilization may not be able to maintain itself. The types of measures we have discussed so far in this series of papers can only arrest the rise in CO_2 concentration — they cannot reduce it. Hence the need for carbon sequestration.

There are two ways in which biomass power could conceivably become carbon negative. One is to use carbon capture and storage (CCS) technology at each power station, pumping the carbon dioxide produced deep underground. This, however, would be a costly option. The optimum size for a biomass energy facility is generally small because feedstock transportation costs set a limit on the distance from which biomass can be brought. The added cost of CCS for a small power station (even assuming that this technology reaches the point where it can demonstrate full technical viability and components can be mass-produced) would almost certainly be prohibitive. Furthermore, not all power stations would be in geologically-suitable areas.

The earth's natural systems sequester carbon in forests, in other plant life, and in soil. These massive carbon sinks are vital to the survival of life on earth, and their enlargement would be highly desirable. However, attempts to do so face enormous difficulties in pressure from competing land uses and a growing world population. (Further detailed discussion of reafforestation and of change in agricultural methods is beyond the scope of this paper.)

The second way in which biomass power can contribute to carbon sequestration requires a more direct "collaboration" with these natural systems. It is also simpler — collect charcoal (biochar) produced by pyrolysis, and return it to the soil. This potentially could bring several benefits: enhanced long-term soil fertility, reduced nitrogen and phosphate run-off, reduced soil emissions of greenhouse gases, stable carbon sequestration, and the freeing up of a larger

quantity of crop residue for power generation. As a recent report puts it, biochar "seems to offer a way to mitigate climate change, produce energy and increase agricultural productivity through a single set of practices or technological applications that interact synergistically".[49]

Biochar remains stable in soils for hundreds of years. Biochar-rich dark earths (terra preta) have been found in several locations in the Amazon basin, a remarkably persistent (and beneficial) remnant of the cultivation methods of pre-Columbian civilizations.

Intensive study of terra preta has led to a realization that biochar is a valuable soil enhancer. This view is backed up by recent research at academic institutions worldwide, as well as by traditional use of charcoal in various parts of the world (including West Africa, Japan and parts of India). Biochar consists primarily of elemental carbon, with an open molecular structure which can function as a "storage facility" for soil nutrients. It is not itself a fertilizer, but a means of holding nutrients within the soil — hence good results are achieved with biochar in field tests only if it is "charged" with manure or compost before application. It also assists in holding water and in providing refuge space for beneficial soil bacteria. Thus addition of biochar to soil can enable stable long-term fertility.

For the same reason, run-off of nutrients — and hence the damage to freshwater ecology which it causes — is lower in soils containing biochar. Both nitrate and phosphate leaching result in eutrophication of lakes and slow-flowing rivers. Phosphate leaching is a double problem, in that there is no natural process which can replace this nutrient in the soil at the rate at which it is being lost in many parts of the prairies. Besides reducing these losses of dissolved nutrients, biochar also reduces atmospheric losses, including emissions of greenhouse gases nitrous oxide and methane.

Because biochar remains stable for so long, there is reason to hope that it will prove a superior carbon sequestration option to current practices such as no-till (in which crop residues are left to decompose in the field, and some carbon becomes incorporated into the soil) or digging in straw. The carbon in uncharred organic material is lost rapidly through microbial action, whereas biochar can remain in the soil for hundreds of years.[50] (This microbial action, which is important to soil fertility, still takes place in the organic carbon fraction of biochar-rich soils: indeed, by providing a refuge for microbes, the biochar appears in many cases to significantly increase the microbial action and with it the yields achieved.[51]) For this reason, biochar could enable substantial quantities of crop residues — far more than those assumed on page 13 — to be released for energy production. Instead of leaving straw to decompose naturally, it would be pyrolysed, with energy produced from the volatile fraction, and stable biochar carbon returned to the soil.

The specific claims made for biochar have been well-documented,[52] but many questions remain as to the viability of practical and widespread application. In addition, it is important to note that the rules for sustainability set out on pages 11-12 should apply to biochar projects just as much as to any other biomass scheme. The precautionary principle should be observed. While the welfare of human civilization depends vitally on avoiding runaway climate change, it also depends on maintaining food-producing soils in an excellent condition.

Biochar has been extensively criticized by a small number of environmental activists and groups associated with the organization BiofuelWatch (BFW). This group has legitimate concerns about the potential negative impacts of poorly-conceived biofuels projects, especially in low income countries. Removal of old-growth forest in order to grow biochar plantations would be grossly irresponsible, for example. However, much of BFW's writing about biochar has been marked by significant inaccuracies, and a failure to recognize the growing number of good examples of non-exploitative biochar projects. Detailed and technically sound rebuttals have been made by biochar practitioners and supporters.[53] However, it is fair to say that the international biochar community has not yet reached a common understanding as to what constitutes sustainable development in practice. For that reason, it is important that there be deliberate thinking about the economic, commercial, social and ecological framework in which practical biochar projects may be conceived in Saskatchewan. The "sustainability rules" set out in this paper are a contribution towards that process.

Biochar is just beginning to move into the stage of large-scale implementation. A 500 kW gasification/pyrolysis power station with limited biochar production has now been opened in California.[54] The use of gasification as part of the process — which results from a choice to optimize for maximum energy production rather than for maximum biochar — limits the amount of biochar produced in this particular plant. In all such projects there will be an element of "trade-off" between these two products. Processes which result in combustion of a higher proportion of the carbon in the biomass will result in more energy output but less biochar. Likewise, processes designed for biochar production will burn less carbon and so produce less energy.

Given the importance of soils, agriculture and ecosystems to future human survival, it would be naive to assume that this trade-off can be managed exclusively by the market. It is highly unlikely that market mechanisms could be devised which ensure optimum, but not excessive use, of biomass, and which balance properly the needs to soils and energy production (at the same time as meeting those of investors). Government regulation, based on the best available scientific advice, will be necessary to ensure good practice which balances energy and land needs. Government incentives will need to be constructed so

Yamagata Biomass Gasification Power Plant in Japan.

as to encourage only those schemes which meet ethical criteria such as those presented in this paper.

I conclude this section with a speculative calculation. The figures may not be accurate, but they give a rough impression of the sort of contribution which the pyrolysis/biochar option could conceivably make:

Let us assume that 10 million tonnes of crop residue is now available for biomass power generation — as biochar can then replace straw currently used for soil protection (or just burnt). If 40% of the energy from this resource (the gaseous product, plus some of the bio-oil broken down into gas by further processing) is available for electrical generation, at an efficiency of 35%, the energy yield will be of the order of 6000 to 7000 GWh/yr. With the higher efficiencies obtainable at CCGT plants, this could perhaps be raised as high as 10000 GWh/yr. Hence biochar, if found to be viable on this scale, may enable us to close the gap between demand and sustainable supply.

At this point, it is not at all clear that this volume of crop residue could be pyrolysed sustainably, and within the limits set by our ethical criteria. This would depend on a range of factors, including the impact of biochar on crop growth rates in Saskatchewan soils, the necessity (or otherwise) of nutrients to "charge" the biochar, the development of suitable methods for incorporating it into the soil, etc. While much research has been done on biochar worldwide, little of it applies in detail to Saskatchewan conditions. Hence discussion of the possibilities offered by biochar is still somewhat speculative. Caution is necessary, but it would be foolish not to actively pursue further research into this option.

Conclusions and Recommendations

As articulated previously in this series, variable renewables — specifically wind and photovoltaics — are vital to the development of a sustainable energy future for the province. One of the next tasks to be undertaken by Green Energy Project Saskatchewan is detailed engineering analysis of the impact of these variable sources on the Saskatchewan grid, and the capacity of different dispatchable options — together with storage and demand shifting — to compensate for that variability. This will enable a degree of quantitative precision which is not yet possible. However, some interim conclusions are possible at this stage:

SaskPower should actively seek an enhanced electricity trading arrangement with Manitoba, and should seek terms which create the future possibility of the export of surplus wind power as well as the import of hydro-generated power to enable the matching of supply with demand.

SaskPower should actively seek partnerships with First Nations and Métis communities with a view to equitable and sustainable development of hydroelectricity in their territory.

Further university research and development is justified in a number of areas, including concentrating solar power, hybrid power stations, storage options, smart grid technology, and especially biochar.

SaskPower should research the best technology on the international market for pyrolysis and gasification of organic materials. The government of Saskatchewan should then seek to make deals with suitable companies to establish a manufacturing base within the province.

Biomass energy works best on a local community scale, as this avoids high transport costs and complex distribution infrastructure. The formation of biomass energy companies under local cooperative or democratic ownership should be encouraged to facilitate the development of the sector on an appropriate scale.

In the short term, government incentives are justified for community-owned and -managed biomass power, provided that it provides dispatchable power with the most efficient technology available.

Electrical generation — even with the most efficient combined cycle gas turbine (CCGT) plants — is inherently inefficient. Typical small power plants will achieve 35% efficiency; CCGT plants may manage 50% efficiency or higher. However, the energy which would otherwise be wasted can be used for space and water heating in local facilities through CHP (cogeneration) schemes. This option should be actively considered for every new biomass power station.

All biomass developments in the province should be required to comply with the criteria set out on pages 11-12:

- A large life cycle energy return on investment (EROI), calculated on a full life cycle analysis.
- Substantial net reductions in greenhouse gas emissions, taking all GHGs into account, and calculated on a full life cycle analysis.
- To avoid dishonest carbon accounting, schemes should not depend on offsets.
- First Nations and Métis livelihood and traditional ways of life should be protected, treaty obligations observed, and genuine consultation carried out.
- Policies should not be pursued which threaten the livelihood of family farms.
- There should be no net reduction in food production as a result of biomass schemes.
- There should be no added threat to important wildlife habitats or to biodiversity.
- There should be no export of the natural means of ensuring soil fertility out of Saskatchewan.
- Saskatchewan should not benefit from the loss of the natural means of ensuring soil fertility in other jurisdictions.
- Nutrients removed from the natural cycle by biomass harvesting should be returned to the soil.

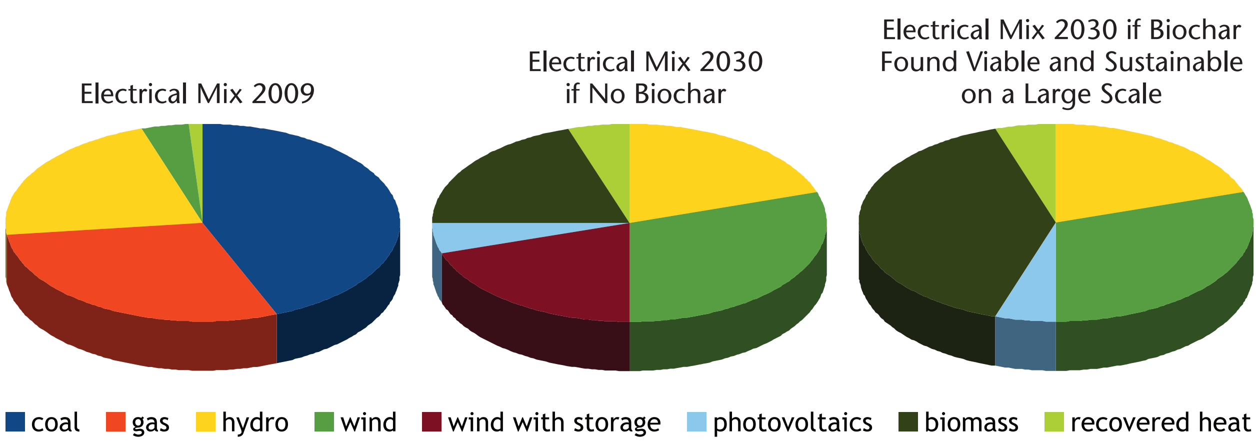
In order to ensure that these criteria are consistently observed, government regulation, based on the best available scientific advice, will be necessary to ensure that both energy and food production move towards sustainability.

It is the function of government to protect its citizens — in this case, to protect future generations from the impact of climate change and resource depletion. Government — including the state-owned power corporation — has a duty to plan a total phase-out of fossil fuel use, and to actively pursue the truly sustainable options discussed here, as well as the efficiency measures, conservation, load shifting, wind power and photovoltaics discussed in previous papers in this series.

How Might the Fuel Mix Look in 2030?

No precise figures are possible at this stage of Green Energy Project Saskatchewan's research. However the pie charts in figure 2 give an indication of the way in which the power mix might change as a result of the approach we have advocated in these papers:

Figure 2: Proposed Transformation of the Saskatchewan Generating Mix, 2009-2030



Endnotes

1 Bigland-Pritchard M and Prebble P (2010), Transforming Saskatchewan's Electrical Future – pt 1: Sustainability is achievable, but how do we get there?, CCPA Saskatchewan

2 Bigland-Pritchard M (2010), Transforming Saskatchewan's Electrical Future – pt 2: Using Electricity more Efficiently, CCPA Saskatchewan

3 Bigland-Pritchard M (2010), Transforming Saskatchewan's Electrical Future – pt 3: The Potential for Wind and Solar Power, CCPA Saskatchewan

4 Space does not permit detailed discussion of the main four options — parabolic troughs, parabolic dishes, Fresnel reflectors and power towers. At the time of writing, a useful introductory page is the wikipedia entry for Concentrating Solar Power: *http://en.wikipedia.org/wiki/Concentrating_solar_power*

5 See *http://www.energy.pitt.edu/DocumentLibrary/SolarTower_Juelich.pdf* for details

6 See *http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations*

7 An assessment of the potential for deep geothermal extraction in southern Saskatchewan is provided at *http://www.legassembly.sk.ca/committees/CrownCentralAgencies/Tabled%20Documents/Brunskill_Sk_Gov_Oct_09.pdf*

8 Peters R and Malley L (2008:Jun), Storing Renewable Power — primer, Pembina Institute, pp 11-12. This short paper also provides an excellent general technical introduction to the subject of energy storage for the electricity generation industry.

9 For details of the operation of pumped storage stations, see *http://www.fhc.co.uk/pumped_storage.htm* and *http://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity*

10 See, for example, *http://en.wikipedia.org/wiki/Dinorwig_Power_Station*

11 For further details, see *http://www.mpoweruk.com/flow.htm*

12 For further details, see *http://en.wikipedia.org/wiki/Vanadium_redox_battery* , *http://electricitystorage.org/tech/technologies_technologies_vrb.htm* and *http://www.vrb.unsw.edu.au/*

13 For further details, see *http://en.wikipedia.org/wiki/Sodium-sulfur_battery*

14 For further details, see *http://en.wikipedia.org/wiki/CAES*

15 For further details, see *http://electricitystorage.org/tech/technologies_technologies_flywheels.htm*

16 For further details, see *http://electricitystorage.org/tech/technologies_technologies_supercapacitor.htm*

17 An excellent analysis of the problems inherent in bringing hydrogen and fuel cells into the mainstream is provided in: Romm, Joseph J (2006), The Hype about Hydrogen: fact and fiction in the race to save the climate, Island Press.

18 Ecologo (2010:Nov:17), Environmental Standard Certification Criteria Document CCD-003: Renewable Low-Impact Electricity Products, p21. Available from *www.ecologo.org*

19 SaskPower (2009:Oct:06), Powering a Sustainable Energy Future — the electricity and conservation strategy for meeting Saskatchewan's needs, p14

20 Calculated from data included in Manitoba Hydro (2010), Building a Powerful Future: Manitoba Hydro-Electric Board 59th Annual Report (for the year ended 2010:Mar:31), pp100-101. Available at *http://www.hydro.mb.ca/corporate/ar/2009/publish/files/ar_0910.pdf*. The surplus available for export ranged from 28% to 41% of Manitoba domestic demand for 2006-2010, averaging at 33%

21 From op cit, p103, and from descriptions of water regime management systems at *http://www.hydro.mb.ca/corporate/water_regimes/lake_wpg_regulation.shtml* and *http://www.hydro.mb.ca/corporate/water_regimes/churchill_river_diversion.shtml*

22 See the Youtube videos on the impact of flooding posted at *http://www.youtube.com/watch?v=Cukwb8LRkDY&feature=related* (with "before and after" maps to show areas of flooding) and *http://www.youtube.com/watch?v=-ZpJokWijio* (showing film evidence of flood damage)

23 Rev John Atchison, Very Rev Stan McKay, Helen Norrie and Rev Arie van Eek (2001), Let Justice flow: report of the interchurch enquiry into northern hydro development, Manitoba Aboriginal Rights Coalition, Winnipeg.

24 Chinta Puxley (2011:05:25), Manitoba Hydro Signs $4-Billion Power Deal, *Globe and Mail*. Available online at *http://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/manitoba-hydro-signs-4-billion-power-deal/article2034611/*

25 SaskPower (2010), Securing Tomorrow's Energy Begins Today: SaskPower Annual Report 2009, p29

26 Larry Kusch (2011:Apr:30), "Hydro line to Saskatchewan would cost $40 million, study says", Winnipeg Free Press. Available online at *http://www.winnipegfreepress.com/local/hydro-line-to-saskatchewan-would-cost-40m-study-says-121016914.html*

27 Campbell J E, Lobell D B and Field C B (2009:May:22), Greater Transportation Energy and GHG Offsets from Bioelectricity than Ethanol, Science, vol 324, pp1055-1057

28 Kiel J (2011:Apr:15), Torrefaction for upgrading biomass into community fuel, Energy Research Centre of the Netherlands, presented at EUROBIONET III workshop Bioenergy and Forest Industry, Espoo, Finland.

29 To take an example from each side of the argument:

Stanford researchers David Pimental and Tad Patzek find EROI values to be less than 1 for fermentation ethanol from corn, cellulosic ethanol from switchgrass and wood, and biodiesel from soy and sunflower oils: Pimental D and Patzek D W (2005:Mar), Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower, Natural Resources Research, Vol. 14, No. 1,

A US government study gives an EROI for biodiesel of 3.215: Sheehan J, Camobreco V, Duffield J, Graboski M and Shapouri H (1998:May), Lifecycle Inventory of Biodiesel and Petroleum Diesel for Use in and Urban Bus, NREL for US Department of Energy and US Department of Agriculture, NREL/SR-580-24089 UC Category 1503, p213. This report, however, does not take into account secondary land use change effects — e.g. displacement of food-producing land leading to conversion of native forest to food production, with consequent energy and greenhouse costs.

30 Wara MW and Victor D G (2008:Apr:18), A Realistic Policy on International Carbon Offsets, Program on Energy and Sustainable Development, Stanford University, working paper #74

31 John Vidal (2008:May:26), Billions wasted on UN climate programme, The Guardian

32 Clarens A F, Resurreccion E P, White M A and Colosi L M (2009), Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks, Environmental Science and Technology, vol 44 no 5, pp1813-1819, 2010

33 MacPherson G (1995), Home-Grown Energy from Short-Rotation Coppice, Farming Press Books, Ipswich, England

34 ed Ledin S and Willebrand E (1996), Handbook on How to Grow Short Rotation Forests, Swedish University of Agricultureal Sciences Department of Short Rotation Forestry, for IEA Bioenergy Task VIII (new cultural treatment and yield improvement) and Task XII (short rotation forestry production systems)

35 Johnston M andWismer M, Nipawin Afforestation Project, in World Resources Institute (2006:Oct), The Greenhouse Gas Protocol: The Land Use, Land Use Change and Forestry Guidance for GHG Project Accounting, Worldwatch Institute, New York, pp60-81. By European standards, this is not a short rotation coppice scheme — periods between coppicing are significantly longer than the 2 to 5 years typical for European willows.

36 The controversial report prepared for the Commonwealth of Massachusetts by the Manomet Center highlights this point:

Walker T, Cardellichio P, Colnes A, Gunn J, Kittler B, Perschel R, Recchia C and Saah D (2010:Jun), Biomass Sustainability and Carbon Policy Study, Manomet Center for Conservation Sciences, for Commonwealth of Massachusetts Department of Energy Resources. Available online from *http://www.manomet.org/*

The report assumes biomass energy is to be provided from forest plantations, and finds that wood harvesting results in a massive carbon debt which is not repaid until decades later by forest regrowth. This conclusion, however, is highly dependent on the starting assumptions. For example, conclusions would be different for well-managed plantations in which planting is planned ahead of time with carbon debt repayment in mind — especially for short-rotation forestry crops.

A recent critique of the Manomet methodology may be found at: *http://www.renewableenergyworld.com/rea/news/article/2011/05/how-manomet-got-it-backwards-challenging-the-debt-then-dividend-axiom?cmpid=WNL-Friday-May27-2011*, and another short critique at: *http://www.nxtbook.com/nxtbooks/saf/forestrysource_201009/#/4*

A longer critique is given by: O'Laughlin J (2010:Sep), Accounting for Greenhouse Gas Emissions from Wood Bioenergy: Response to the U.S. Environmental Protection Agency's Call for Information, Including Partial Review of the Manomet Center for Conservation Sciences' "Biomass Sustainability and Carbon Policy" Study, Report No. 31, Policy Analysis Group, College of Natural Resources, University of Idaho

37 Amon B, Kryvoruchko V, Amon T and Zechmeister-Boltenstein S (2005), Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment: Agriculture, Ecosystems and Environment 112 (2006), pp153-162

38 Clemens J, Trimborn M, Weiland P and Amon B (2005), Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry, Agriculture, Ecosystems and Environment 112 (2006), pp171-177

39 Monteney G-J, Bannink A and Chadwick D (2005), Greenhouse gas abatement strategies for animal husbandry: Agriculture, Ecosystems and Environment 112 (2006), pp163-170

40 Sommer S G, Petersen S O and Møller H B (2006), Algorithms for calculating methane and nitrous oxide emissions from manure management, Nutrient Cycling in Agroecosystems 69 (2006), pp143-154

41 Thomsen I K, Pedersen A R, Nyord T and Pedersen S O (2009), Effects of slurry pre-treatment and application technique on short-term N2O emissions as determined by a new non-linear approach: Agriculture, Ecosystems and Environment 136 (2010), pp227-235

42 Turnbull J H and Kamthunzi W (date unknown), Greenhouse gas emission reduction associated with livestock waste management systems: a case study for the Langerwerf dairy waste management system, Peninsular Energy Partners (Los Altos, CA, USA) and Bunda College (Lilongwe, Malawi)

43 Taken from analysis of data in: Sokjansanj S, Mani S, Stumborg M, Samson R and Fenton J (2006), Production and distribution of cereal straw on the Canadian prairies, Canadian Biosystems Engineering, vol 48, pp3.39-3.46

44 Stumborg, M., Townley-Smith, L. and Coxworth, E. (1996). Sustainability and economic issues for cereal crop residue export. Can. J. Plant Sci. 76: 669-673.

45 *http://www.fsccanada.org/fmstandards.htm*

46 For example, the city of Bristol, England, has long operated an AD plant at its municipal sewage works. Recent developments there are described at *http://blog.monsal.com/index.php/news/biogas-taken-from-monsals-advanced-digestion-plant-in-bristol-run-by-geneco-a-subsidery-of-wessex-water-powers-vw-beetle/*

47 For an example in the English midlands, see *http://www.biffa.co.uk/waste-processing/food-recycling/poplars-ad.html*

48 The recent work of leading climate scientists such as Jim Hansen (head of the NASA Goddard Institute for Space Studies and Adjunct Professor at Columbia University Earth Institute) is increasingly showing that internationally-adopted targets for atmospheric carbon dioxide and temperature peaks (450 ppm CO_2 equivalent, 2°C temperature elevation) are inadequate. Hansen is calling for a programme to reduce atmospheric carbon dioxide from its present value of between 390 and 395 ppm to 350ppm or less. Hansen has recently made significant efforts to explain climate change to a wider public. Some key documents are:

Hansen J E (2008), Target atmospheric CO_2: Where should humanity aim?, Open Atmos Sci J, vol.2, pp217-231. Available online at *http://arxiv.org/abs/0804.1126 (main article) and http://arxiv.org/abs/0804.1135* (supporting material)

Hansen, James (2011:Jun:03), Silence is Deadly. Available online at http:/*/www.columbia.edu/~jeh1/mailings/2011/20110603_SilenceIsDeadly.pdf*

Hansen J, Kharecha P, Sato M, Epstein P, Hearty P J, Hoegh-Guldberg O, Parmesan C, Rahmstorf S, Rockstrom J, Rohling E J, Sachs J, Smith P, Steffen K, von Schuckmann K and Zachos J C (2011:05), The Case for Young People and Nature: a path to a healthy, natural , prosperous future. Available online at *http://columbia.edu/¬jeh1/mailings/2011/20110505_CaseForYoungPeople.pdf*

Hansen, James (2010:Oct:27), Human-Made Climate Change: a moral, political and legal issue, Blue Planet Lecture, Tokyo, Japan. Available online at *http://www.beunder.com/pdf/BluePlanetLecture.pdf*. A video of a later presentation of the same material is available online at *http://www.youtube.com/watch?v=CcPMak6YvDE*.

Hansen J E and Sato M (2009), Paleoclimate implications for human-made climate change. Available online at *http://arxiv.org/abs/1105.0968*

Hansen J E, Sato M, Kharecha P and von Schuckmann, K, Earth's Energy Imbalance and Implications. Available online at *http://arxiv.org/abs/1105.1140*

Rockström J., Steffen W, Noone K, Persson Å, Chapin F S III, Lambin E, Lenton T M, Scheffer M, Folke C, Schellnhuber H, Nykvist B, De Wit C A, Hughes T, van der

Leeuw S, Rodhe H, Sörlin S, Snyder P K, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell R W, Fabry V J, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, and Foley J (2009), Planetary Boundaries: Exploring the Safe Operating Space for Humanity, Ecology and Society 14(2): 32. Available online at *http://www.ecologyandsociety.org/vol14/iss2/art32*. An outline of this paper, together with video presentations, is available at *http://www.stockholmresilience.org/planetary-boundaries*

Gillett N P, Arora V K, Zickfeld K, Marshall S J and Merryfield W J (2011:Jan:09), Ongoing climate change following a complete cessation of carbon dioxide emissions, Nature Geoscience Letters

49 Leach M, Fairhead J, Fraser J and Lehner E (2010), Biocharred Pathways to Sustainability?: Triple Wins, Livelihoods and the Politics of Technological Promise, STEPS Centre, University of Sussex, Brighton, England

50 Baldock J A and Smernik R J (2002), Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood, Organic Geochemistry vol 33 (2002) pp 1093–1109

51 See, for example, Kimetu J M and Lehmann J (2010), Stability and stabilisation of biochar and green manure in and with different organic carbon contents, Australian Journal of Soil Research, vol 48,pp577-585

52 The scientific literature on the subject has grown very considerably in the last few years, and understanding of the subject is growing fast. Instead of picking any individual papers (which will be rapidly superseded by new knowledge), I instead refer the reader to a few reliable sources:

The International Biochar Initiative exists "to promote the development of biochar systems which follow Cradle to Cradle sustainability guidelines". Its website contains a wide variety of resources, and may be found at *http://www.biochar-international.org*.

At the time of writing, the most comprehensive treatment of the subject is:

ed. Lehmann J and Joseph S (2009), Biochar for Environmental Management: Science and Technology, Earthscan, London, England / Sterling, VA, USA

In addition, both technical and non-technical readers can learn from two popular/policy treatments of the subject:

Bruges, James (2009), The Biochar Debate: charcoal's potential to reverse climate change and build soil fertility, Green Books, Totnes, England / Chelsea Green, White River Junction, VT, USA

Bates, Albert (2010), The Biochar Solution: carbon farming and climate change, New Society Publishers, Gabriola Is, BC

53 The BiofuelsWatch case is set out in Ernsting A and Smolker B (2009:Feb), Biochar for Climate Change Mitigation — fact or fiction?, available for download from *http://www.biofuelswatch.org.uk/*

A concise but reasonably comprehensive response is provided by Mulcahy D N and Mulcahy D L (2010:Jul), Biochar Can Help Save the World, available for download from *http://www.worldstove.com*. The International Biochar Initiative have also published their own response at *http://www.biochar-international.org/sites/default/files/Biochar%20Misconceptions%20and%20the%20Science.pdf*

Useful discussion of policy options is also to be found in Leach et al (ref 44) and Bruges (ref 52).

54 PR-USA.net (2011:May:20), 500 kW Biomass Gasification Plant Achieves Significant Milestone by Successfully Passing Interconnec. Available online at *http://pr-usa.net/index.php?option=com_content&task=view&id=740020&Itemid=29*. Further details of the plant available at *http://www.phoenixenergy.net/biomasspower.html*