The Evolution of Electricity

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Since the industrial revolution which began in the late 1700's, societies throughout the world have become increasingly reliant on energy derived from sources other than the muscles of humans and animals. In fact the industrial revolution was in great measure the result of harnessing energy resources for the first time. That's not strictly true of course since sailing boats are as old as mankind and water wheels have been used to lift irrigation water for millennia but it was the harnessing of energy sources on a massive scale that led to the industrial revolution and the modern world as we know it.

And what is that world? It is a world markedly different to mediaeval times which preceded the industrial revolution where the majority of the population were illiterate and worked their entire short lives as virtual slaves to support a few intellectuals and rulers. The industrial revolution made a step-change in the economic surplus created by human endeavour and that surplus has progressively become more widely available so that today we collectively enjoy unprecedented discretion in how we spend our time and efforts. Over the last two centuries, using energy resources to leverage the time and effort of human beings has become fundamental to our way of life.

The early days of the industrial revolution revolved around applying energy to mining and manufacturing which allowed for point sources of energy to be developed. Thus, many industrial towns were located near falling water. St. Catharines is a good example of that and if you look closely, water driven mills and their remnants are located in the downtowns of many Ontario communities.

Many manufacturing processes, and of course all mines, did not have flexibility to locate beside energy sources and so wood or coal-fired steam engines became important. Thermally generated energy came into being because it allowed fuel to be transported to where energy was needed. Coal quickly came into widespread use since it packs more energy per pound than wood and so reduced the cost of energy transport.

But steam engines and water wheels are expensive to build so economics mitigated against building small ones. Energy use therefore continued to be confined to industrial applications in a relatively few locations and, for the most part, individuals still relied on the mediaeval model of muscle power.

Then during the closing decades of the 1800s and the early decades of the 1900s the electric revolution democratized energy use. For the first time, energy became widely available to individuals and businesses of all sizes. Like many changes, the introduction of electricity occurred not due to an individual action, innovation or invention but rather due to the convergence of a number of innovations and opportunities.

One of the innovation threads was playing out at Niagara Falls where on the US side of the river, all the land close to the falls was occupied by industries needing ready access to the falling water for their source of energy. Landowners and industries began looking into ways of moving some of the immense amounts of energy that could be developed at the falls to locations farther afield. Moving the energy would, in one stroke, make better use of the crowded and expensive land near the falls and increase the value of energy-impoverished land more remote from the falls. As we can now see today, the winning combination was to generate electricity on the scarce land close to the source of energy and distribute that electricity to where it was used.

Another of the innovation threads was playing out in a number of the world's major cities where the invention of the incandescent light bulb provided a better alternative for lighting buildings than the coal-gas flames that dominated. While Thomas Edison is probably most closely associated in peoples' minds with the invention of the incandescent bulb, I believe his real genius was adopting an established business model because Edison did not attempt to sell electricity but rather, like the gas companies, offered a lighting service.

Instead of distilling coal to make gas which was then distributed in pipes to light residences and businesses in the neighbourhood of the distillation plant, Edison burnt coal to make electricity which was distributed in wires to light residences and businesses in the neighbourhood. In both cases, customers received lighting service fuelled by coal so their buying decision revolved around the quality of the lighting provided rather than the technology involved.

These two threads – centralized conversion of an energy resource into electricity and the distribution of electricity to end users – came together just over a century ago to become what we now know as an electric utility. It is instructive to look at some of the implications of this convergence because many of our future energy options depend on where we are and where we are depends on how we got here.

Firstly, electricity has become a commodity where once it was a specialized vehicle for moving energy between industrial sites or one of two alternative intermediate steps in providing domestic lighting service from coal. With the arrival of electric utilities, we put in place a system which allowed harnessing many different sources of energy and distributing this processed energy very broadly for a variety of end uses.

Its ready availability in both large and small quantities means that electricity became intricately and ubiquitously intertwined with all elements of our everyday life. Long gone are the days when electricity meant industrial processes or domestic lighting. Today it is an essential component of everything we do in commerce, health care, entertainment, transportation and manufacturing. In effect, electricity became an energy currency – something of no use in itself but widely used as an intermediary in exchanges between sources and end uses.

We don’t have to look very far for examples of just how dependent our societies have become on a reliable source of energy in the form of electricity. In the ice storm which hit eastern Ontario and western Quebec in 1998 the City of Montreal hung by a thread as the physical collapse of the electricity system resulted in there being only a single transmission line supplying the entire city. Without that line, as emergency diesel generators used up the few hours of fuel they store, there would be no water supply and without water there could be no fire fighting. Should fire have broken out, which was a higher risk than normal as residents reverted to woodstoves and candles in the absence of their customary electric heating and lighting, chaos and carnage would have ensued as people attempted to escape along unlit streets littered with fallen branches.

The weather was kinder in the August 2003 blackout which affected 50 million people for 4 days in southern Ontario and the northeast US. In Toronto, transit shut down with thousands trapped underground in stranded subway trains and others abandoning streetcars frozen in their tracks blocking the way of conventional traffic. That conventional traffic, including taxis, got thinner as the days wore on since they ran out of fuel and fuelling stations lacked electricity to operate pumps. The resulting reduced traffic volume was a blessing in disguise since electrically powered traffic control systems had stopped working. High rise commercial buildings became inoperable as they drained their emergency fuel supplies within a few hours leaving their vast interior spaces uninhabitable since they were designed to rely on electrically powered lighting, ventilation and elevators.

In both of these recent events, life as we know it became unsustainable within a few hours of the loss of the electricity supply.

One of the consequences of commoditizing anything is that it increasingly isolates the end user from the supplier. In fact of course that is the very definition and essence of a commodity – a good or service that is not differentiated between suppliers. In such circumstances price becomes the only differentiator guiding purchasing decisions and suppliers focus on reducing the costs of their production in concert with consumers’ desire to pay no more than necessary. I point this out because the electricity system we have today is in fact the most economical one possible – the commoditization of electricity followed by a century of commercial investment and operation has ensured that.

What are the characteristics of that electricity system and where does that put us in terms of continued evolution of our energy future? Firstly, it is a highly centralized system. Economies of scale and the difficulty of storing electricity have ensured that. Our system today is based on large central generating stations transmitting bulk power over long distances to major load centres where it is subdivided and distributed to individual end users.

This has proved to be the lowest cost approach given that storing electricity is quite difficult and expensive. The way we most commonly consider of storing electricity – the rechargeable battery we have in our cars and electronic gadgets – actually involves a chemical energy conversion process. In fact, virtually all so-called electric storage technologies involve conversions to other forms of energy and those conversions are expensive both for the equipment and materials involved and for the loss of energy in the two-way conversion process.

So here is a manufactured product – electricity – which, as it turns out, is more expensive to store than to manufacture – a product where the warehouse is more expensive than the factory. Under those conditions, economics drives it towards being a just-in-time product – we make it when we need it. Electricity is really the ultimate just-in-time product and today our electricity systems have no storage capability at all. Instead, they are planned, designed and operated to respond to the constantly varying requirements of users by employing a variety of different types of generators.

Some generators are optimized to provide vast quantities of energy at a low cost while others are optimized to respond rapidly to changing needs. Between these extremes are the generators optimized to follow slower and longer term trends by producing moderate amounts of electricity that distinguish, for example, morning requirements from afternoon requirements. Notice that I said "optimized" – this means economically optimized.

To keep costs as low as possible, the large "baseload" generators, which are optimized to operate flat out, should clearly use a low cost fuel but since they can spread their initial construction cost over a large number of production units they can afford to be more expensive to build. At the opposite end of the extreme, the rapidly responding "peaking" generators are not expected to operate for many hours or produce much electricity so they need to be designed for low construction cost but will not be critically disadvantaged by using expensive fuel if necessary.

Orchestrating this range of resources into the most economical supply to consumers requires a central system operator. The role of that operator is to ensure that on a moment by moment basis supply exactly matches demand in every part of the overall system and that that matching is done in the most economical fashion. So you can see that the consequence of commoditizing electricity and not having an economical way of storing it is a very centralized system.

Now let's reflect on the future. The current top of mind issue with regards to the going-forward perspective on energy is climate change. The dominant consensus is that climate is changing due to release of carbon dioxide from man made activities – primarily the burning of carbon based fuels for energy. I will not get into this any more deeply than to observe three things.

Firstly, this cause and effect model is very simplistic in the context of the complex multilateral interactions that are typical in natural systems. This tells me that we have more to learn about climate change. Secondly, it is obvious that we cannot expect that there will be no impact if, over the course of a few decades, we release into the natural environment carbon that has been sequestered over many millennia. Thirdly, since in democracies changes in collective behaviour are facilitated by a sense of crisis, it is good that the simplistic model has taken hold since it creates the conditions necessary for change in our use of fossil fuels.

How do we bring about that change with respect to electricity? In my view, we need to put a price on carbon such that its use gets factored into the go-forward decisions. This would have the advantage of continuing a century of economically rational development of what has become an essential underpinning of modern society – the electricity system. In fact, to do otherwise than proceed on an economic basis is to risk massive dislocations both within our own economy and with respect to the economies of other countries.

Frankly, the process of picking winners and losers in renewable electricity technologies as a matter of policy puts us all at a considerable risk because it will inevitably make electricity more expensive than it needed to be for the particular target carbon diet. Increasing the cost of electricity relative to other sources of energy by making arbitrary technology choices will both reduce the role that electricity can play in reforming our energy use patterns and will also put our entire economy at a disadvantage to other countries that do stick to economically rational approaches.

The pushback on putting a price on carbon is of course that it increases the costs for all of us in everything we do. But given that we have the most economical energy supply possible now, any change we make will put the cost up. The case for pricing carbon is simply that it brings with it the promise that the costs will go up by the minimum amount possible.

As an aside, we should all be wary of the fact that policy makers are leaning toward tasking electricity with carrying the lion's share of reducing our carbon diet. This makes sense in that its highly centralized structure simplifies the logistics for making changes. But it doesn't make sense in terms of dealing with the biggest use of fossil fuels which is the transportation sector. At its highest, Ontario's electricity sector contributed about 20% of the manmade carbon dioxide emissions and it is on track to producing only 5% by 2014. The biggest share of the balance is contributed by the cars and trucks we all drive which collectively make electricity's contribution seem small.

It is therefore clear that a switch from fossil fuel to electricity will reduce our carbon footprint and we should be doing all we can to expand the supply and use of electricity. That will only happen if we do not put price barriers in the way and price barriers will be avoided only if we put a price on carbon and refrain from policy initiatives which pick winning and losing technologies – choices which will inevitably cost more than necessary to meet emission targets.

The second most prevalent consensus in reforming our electricity system is the need to enable small-scale distributed generation. It is argued that this will increase reliability by reducing the brittleness that goes with a large centralized approach. It is also reasoned that this will reduce costs by reducing the need for "wires" and particularly long distance transmission. By manufacturing electricity close to where it is used, a long distance bulk transportation system should become redundant or at least less important.

There are elements of truth to this reasoning but, again, I would caution against a rush to judgement in the face of economic and physical realities. As I have outlined, the centralized system we have is the result of rational development in an economic framework constrained by the laws of physics. For any type of generator there are economies of scale and so the maximum size is limited by the proportionately increasing cost of the transmission and distribution network required to deliver production to users. Obviously the bigger the generator the more users it needs to reach and given that, from the perspective of the electricity system, population densities are fixed, then bigger generators need bigger investments in transmission facilities.

For each type of generating technology, a balance is reached which results in the lowest cost of service to customers. Nuclear and large hydro electric generators have strong economies of scale and can therefore justify major investments in transmission to serve large numbers of customers. Natural gas fired generators achieve economies of scale at much smaller sizes. But the economies of scale for generators using renewable sources of energy are smaller yet because they are governed by the low densities of those energy sources. Let me expand on that statement and its implications.

Sources of energy such as wind and solar are very diffuse compared to nuclear, hydroelectric, or fossil fuels. Biofuels too yield lower energy per unit of weight or volume than do fossil fuels. This is the fundamental reason why we have not seen much use of these energy sources over the last century of electricity system development. It is more economical to make electricity from concentrated sources of energy than diffuse sources for a variety of reasons.

To begin with, for a given rating, the size and therefore cost, of the machinery is much lower when, for example, high density water is used to spin a turbine instead of low density air. Coal is really the result of solar energy that has accumulated over the millennia through photosynthesis in plants so it should be no surprise that it is higher in energy density that sunshine falling in real time or biofuel crops that have seen one or only a few growing seasons.

Adopting renewable energy technologies therefore will result in a lower average overall energy density in the supply system – basically a larger number of smaller generators than presently exists. This will require the development of gathering systems which presently do not exist in the electricity system. What we do have is distribution systems that in many cases occupy the same locations as required for gathering renewable energy supplies. But as the name implies distribution systems have been designed to operate unidirectionally and considerable upgrading and investment will be required to repurpose them as gathering systems to connect in renewable generation spread over wide areas.

This is actually one of the main objectives of the so-called "smart grid" concept which is being increasingly talked about. The distribution system is the dumbest part of the existing electricity system and needs to be considerably enhanced in both physical capacity and controllability to become a gathering system for significant amounts of renewable energy.

This is an almost endless and fascinating topic and I could go on. I haven't addressed the issue of electricity supply reliability, its importance and value and how to achieve it most economically. We haven't touched on electricity and transportation in all its flavours – hybrid vehicles, plug-in hybrid vehicles, electric vehicles with gasoline assist and pure electric vehicles. Neither have we touched on alternative energy currencies to electricity such as hydrogen. We haven't explored alternative ways of putting a price on carbon – tax, cap-and-trade or some hybrid like a tax with tradable tax credits. But let me stop here by underlining one point that I believe should be fundamental to all our energy policy initiatives.

And that point is that we need to facilitate rational economic development and avoid bonusing or taxing particular technological approaches. The temptation to implement a particular solution is great because it creates a sense of achievement and accomplishment which is consistent with the sense of crisis driving change.

In contrast, relying on economic pressures produces relatively invisible and slow incremental change. But I submit to you that those economically driven changes will be more substantial and sustainable precisely because they have been economically driven and therefore mesh with the myriad other changes that will inevitably happen in society.

In fact, to rely on anything other than economic forces could easily result in change consisting of a series of isolated anomalies that create the very disconnects and discrepancies which will lead to retrenchment. And for electricity in particular, its ubiquitous nature will magnify the effect of any such retrenchment on our general well being as a society.