Advanced Energy Generation Technologies with Potential to Mitigate Greenhouse Gas Emissions

by

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Abstract

Global greenhouse gas (GHG) reduction targets to prevent widespread catastrophic climate change require a global switch to low and zero emission electricity and heat generation technologies within a very limited timeframe. GHG mitigation technologies have different profiles for offering base load electricity and different expected levelized unit costs. A literature review and elite interviews are conducted to assess the economic competitiveness and technical viability of various technologies, both established and emerging, with especial attention to views that dissent from the prevailing orthodoxy. Advanced CANDU reactors embody important advances that make them potentially competitive with natural gas fired electricity generation. Wind is economically and technically feasible up to 20% of a typical national jurisdiction's energy mixture. Solar and other renewables suffer from considerable economic and technical barriers that preclude significant market penetration.

Keywords: Levelized cost of electricity; alternative energy technologies; economic competitiveness; thermonuclear fusion power; advanced nuclear economics;

For Angie

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Table of Contents

List of Tables

List of Figures

List of Acronyms

CO_2	Carbon Dioxide
LCOE	Levelized Cost of Electricity
MCF	Magnetic Confinement Fusion
ICF	Inertial Confinement Fusion
MTF	Magnetized Target Fusion
GHG	Greenhouse Gas
kWh	Kilowatt hour of electricity
MWh	Megawatt hour of electricity (1000 kWh)
TWh	Terawatt hour of electricity (1000 GWh)
KW	Kilowatt
MW	Megawatt (1000KW)
GW	Gigawatt (1000MW)
TW	Terawatt
Mtoe	Million tonnes of oil equivalent
NIMBY	Not In My Back Yard
NAMBY	Not In Anyone's Back Yard
PV	Photovoltaic
CSP	Concentrated Solar Power
U^{233}	Uranium 233
U^{235}	Uranium 235
P^{239}	Plutonium 239
IEA	International Energy Agency
EIA	Energy Information Administration
NREL	National Renewable Energy Laboratory
CAES	Compressed Air Energy Storage
BTU	British Thermal Unit
MMBTU	One million British Thermal Units
CCGT	Combined Cycle Gas Turbine
OECD	Organization for Economic Co-Operation and Development
AC	Alternating Current
DC	Direct Current

ITER	International Thermonuclear Experimental Reactor
USD	United States Dollars
EFDA	European Fusion Development Agency
DEMO	Demonstration Reactor
CanWEA	Canadian Wind Energy Association
LNG	Liquefied Natural Gas
CANDU	Canada Deuterium Uranium (Reactor)
SMR	Small Modular Reactor
SDTC	Sustainable Development Technology Canada
TWP-R	Travelling Wave Prototype Reactor

1. Literature Review

1.1. Introduction

The Copenhagen Accord of 2009 recognized the scientific consensus that global temperature increases should be kept below 2 degrees Celsius to prevent widespread potentially catastrophic consequences for human life on Earth (United Nations, 2009). The International Panel on Climate Change has stated that to meet this requirement, atmospheric levels of greenhouse gasses will have to be maintained below 450 ppm CO2 equivalent, and future emissions will need to be stabilized at 85% below 2000 levels by 2050 (IPCC, 2007). These restrictions require a global switch to low-emission electricity and heat generation technologies within a very limited timeframe. This literature review assesses the existing work on the viability of established and emerging methods of electricity and heat generation as to their potential contribution to the mitigation of greenhouse gas emissions, with especial attention to their capability to become economically competitive with fossil fuel generation. The review will address the potential for the following:

- solar (both photovoltaic and thermal);
- nuclear (both conventional and advanced);
- geothermal, and
- wind technologies.

If we ignore the external cost of climate change, the lowest levelized cost per kilowatt hour of electricity is, in most circumstances, to burn a fossil fuel such as coal or natural gas (van Ruijven & van Vurren, 2009). Using the TIMER global energy model, Bas et al. (2009) concluded that, in the absence of carbon pricing to significantly increase the financial cost of hydrocarbon fuels, energy producers will switch between natural gas and coal-fired methods of electricity and heat generation throughout this century. In the transportation sector, high petroleum prices lead to a shift to alternatives such as natural gas, coal-to-hydrogen, and biofuels, technologies that also lead to high levels of greenhouse gas emissions (van Ruijven & van Vurren, 2009). With a sufficiently high price placed on carbon emissions, firms will shift electricity production to new technologies, such as natural gas with carbon capture and storage (CCS), GHG mitigation technologies applied to coal with CCS, advanced nuclear, wind, and solar (van Ruijven & van Vurren, 2009). Achieving a sufficiently high carbon price – probably \$100/tonne of CO2 equivalent, ramping up to \$200/tonne over a decade – will require some combination of carbon taxes, and feed-in tariffs to subsidize renewable or clean energy technologies (de Mooij, Parry, & Keen, 2012).

There are multiple assessments that analyze the potential economic competitiveness of emerging and established electricity and heat generating technologies with a high potential for GHG mitigation. These assessments begin however with widely differing assumptions and come to completely different conclusions as to when particular technologies will become economically competitive with fossil fuel generation (Nicholson et al., 2010). For example, one study claimed that Australia could meet all of its energy requirements from a 60:40 combination of solar thermal and wind power (Energy Research Institute, 2010). Critics have questioned the report for discussing technical feasibility of renewable technologies, but not taking adequate account of the economic cost of renewables relative to fossil fuel fired methods of generation (Barton, 2009).[1] It is doubtful that a single magic bullet will be found to achieve the goals of the IPCC within an acceptable timeframe (Center for American Progress, 2006). Probably, a combination of technologies – established, emerging, and expected to-become commercialized – is required to meet these challenges (Akashi et. Al., 2012).

Technology switching depends on several factors. First the technology in question must be commercially available (Lipman, Nemet, & Kammen, 2004). This

[1] Admittedly, the report does in its appendices state that for the plan to be implemented a levelized price for renewables of electricity of \$100/MWh must be achieved through a combination of subsidies and feed in tariffs. In terms of solar thermal power, the implementation of the plan hinges on expected decreases in the levelized cost of solar thermal power brought about by total installed world capacity of solar thermal reaching 8.7 GW (Nicholson., et. al., 2010).

means that the technology cannot be at the prototype stage. (Nicholson, Biegler, & Brook, 2010). Second, the technology should be able to generate electricity or heat at scale, at a cost that is economically competitive with existing methods of fossil fuel fired methods of generation – given the prevailing carbon pricing regime (Center for American Progress, 2006). Finally, public acceptance is important. Firms must mitigate negative impacts of deployment of renewable energy technologies to ensure that they will not be met with significant public opposition (Devine-Wright, 2010).

Each of the different technologies under analysis in this work have different NIMBY (Not In My Backyard) and NAMBY (Not In Anyone's Backyard) profiles in terms of public acceptance. Some of the NIMBY and NAMBY concerns for each of these technologies are more significant and potentially intractable than others. Examples include perceived health impacts of wind farms as a result of the background noise generated by such facilities, public anxiety regarding the potential for catastrophic radiation release from nuclear power plants, and opposition to hydroelectric capacity development due environmental impacts. Research should be conducted as to the effectiveness of public education strategies in mitigating societal opposition to the deployment of various technologies. Such research is beyond the scope of this work, but should be undertaken should governments hope to credibly achieve greenhouse gas reduction targets. This work is concerned with determining the technical viability of established and emerging greenhouse gas mitigation technologies, as well as assessing their economic competitiveness using a convenient measure such as their respective levelized cost of electricity (see below).

1.2. Trends in Levelized Cost of Electricity

Levelized cost per unit of electricity is a convenient measure of the overall relative potential of various energy generating technologies (EIA, 2011). A value for the levelized cost of electricity is derived by calculating the present value of the capital, financing, and operating and maintenance costs of a particular power generation facility that relies on a certain technology (Hazelhurst, 2010). These values are summed and then divided by the "present value" of electricity that will be generated by the facility in each year over its lifetime.[2] This also takes into account the capacity factor of the facility, that is the percentage of hours in a year that the facility can generate the optimized amount of power possible within the facility's tolerances. Electrical generation typically requires very high up front capital costs, with relatively low operating costs over long plant lifetimes. However, electrical generation using fuels subject to volatile commodity markets are exposed to comparably high uncertainty of operating costs (Nuclear Energy Institute, 2008). Historically, public subsidy, regulation and taxes have been able to switch levelized cost rankings between different technologies. Examples include the decisions to construct large hydroelectric projects in British Columbia, the United States, and the former Soviet Union or decisions to abandon high sulphur coal in US power generation.

The levelized costs of electricity for solar (both solar and photovoltaic) and wind technologies have been decreasing for the past twenty years due to advances in technology, efficiency gains through transmission, and learning by doing (EIA, 2011). The rate of decrease in levelized costs of electricity for solar PV, thermal, and wind (both onshore and offshore) has declined within the past ten years and is now approaching zero (NREL, 2010; Texas State Energy Conservation Office, 2005). This implies there may be little further real decline in levelized costs per MWh for these technologies.

Table 1 shows the most recent estimates, made in 2012, by the US Energy Information Agency of anticipated levelized cost of electricity per MWh for multiple competing technologies given plant construction beginning in 2016. It assumes a 3% annual increase in capital cost installation, a 7% real discount rate, and incorporates transmission upgrading costs in the cases of solar and wind (EIA, 2011). The figures provided do not take into account carbon pricing regimes or other penalties for the emission of greenhouse gasses. Natural gas is the technology to beat among competing energy technologies, with an estimated levelized cost of $66/MWh given projected costs of natural gas. Large hydro follows second, with a levelized cost of $86/MWh, followed by onshore wind at $97/MWh, which is then followed by advanced

[2] The "present value" of electricity generated entails discounting electricity generated in different years using the same discount factor applied to calculate present value of costs.

nuclear technologies (which include Generation III and III+ reactors) at $111/MWh. Solar languishes with levelized costs of $152/MWh, and $242/MWh for solar PV. Geothermal costs $98/MWh, and due to the unique siting requirements of geothermal, the EIA is clear that it does not have the potential for global deployment (EIA, 2011).

Table 1 Estimates of Levelized Cost of Electricity for different technologies Source: Energy Information Administration (2012)

U.S. Average Levelized Costs (2010 $/megawatt hour) for Plants Entering Service in 2017

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Dispatchable Technologies						
Conventional Coal	85	64.9	4.0	27.5	1.2	97.7
Advanced Coal	85	74.1	6.6	29.1	1.2	110.9
Advanced Coal with CCS	85	91.8	9.3	36.4	1.2	138.8
Natural Gas-fired						
Conventional Combined Cycle	87	17.2	1.9	45.8	1.2	66.1
Advanced Combined Cycle	87	17.5	1.9	42.4	1.2	63.1

U.S. Average Levelized Costs (2010 $/megawatt hour) for Plants Entering Service in 2017

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Advanced CC with CCS	87	34.3	4.0	50.6	1.2	90.1
Conventional Combustion Turbine	30	45.3	2.7	76.4	3.6	127.9
Advanced Combustion Turbine	30	31.0	2.6	64.7	3.6	101.8
Advanced Nuclear	90	87.5	11.3	11.6	1.1	111.4
Geothermal	91	75.1	11.9	9.6	1.5	98.2
Biomass	83	56.0	13.8	44.3	1.3	115.4
Non-Dispatchable Technologies						
Wind	33	82.5	9.8	0.0	3.8	96.0
Solar PV[1]	25	140.7	7.7	0.0	4.3	152.7

U.S. Average Levelized Costs (2010 $/megawatt hour) for Plants Entering Service in 2017

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Solar Thermal	20	195.6	40.1	0.0	6.3	242.0
Hydro[2]	53	76.9	4.0	6.0	2.1	88.9

[1]Costs are expressed in terms of net AC power available to the grid for the installed capacity. The costs do not include transmission and distribution costs.
[2]As modeled, hydro is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.
Note: These results do not include targeted tax credits such as the production or investment tax credit available for some technologies, which could significantly affect the levelized cost estimate. Source: U.S. Energy Information Administration, Annual Energy Outlook 2012, June 2012, DOE/EIA-0383(2012).

1.3. Wind and Solar

1.3.1. Wind Power

Wind power is the conversion of kinetic wind energy into electrical energy through the use of a device such as a wind turbine. Wind turbines are typically installed in a large series in a geographic region which has favourable overall annual wind conditions. Wind turbines may be located on land, spaced so as not to decrease the kinetic conversion efficiency of the other turbines. Offshore wind turbines are constructed in the sea, where more reliable and high velocity winds are typical throughout the year. Onshore wind turbines are significantly less costly to construct than offshore, due to the extreme conditions inherent to the seas. Wind turbines are almost universal in their design. They are characterized by a vertical pylon upon which sits a nacelle containing a three-blade turbine geared to an electrical generator. Wind turbines are connected to each other by a grid connection and communications network, and the farm itself feeds into a substation located nearby. From there the electricity is transferred by high voltage lines to where it is needed. Wind turbines produce no greenhouse gas emissions when they are in operation, save those generated by the routine maintenance of the turbines and their associated infrastructure.

Considered in the early 1980s to be a fringe technology that would not be able to significantly penetrate global power markets, wind power has in 2012 crossed the 250GW threshold in total global installed capacity (World Wind Energy Association, 2012). Figure 1 shows the estimated levelized cost of electricity for wind power from 1980 to 2009. According to the IEA, since 1980 the levelized cost of wind power has declined from $150/MWh to approximately $50/MWh (National Renewable Energy Laboratory, 2010). Due to a surge in the upscaling of turbines during the mid 2000s, increases in capital costs due to materials scarcity, and increasing demand for turbines in the mid-2000s, the levelized cost of electricity from wind in the short run has increased to approximately $75/MWh at present from an all time low of $50/MWh in the early 2000's (International Energy Agency, 2012). This illustrates a discrepancy in the literature; the Energy Information Administration reports levelized costs of $98/MWh from wind power (see Table 1). The findings presented below were prepared by the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory, the European Wind Energy Association and the Spanish Wind Energy Association for the International Energy Agency (National Renewable Energy Laboratory, 2010).

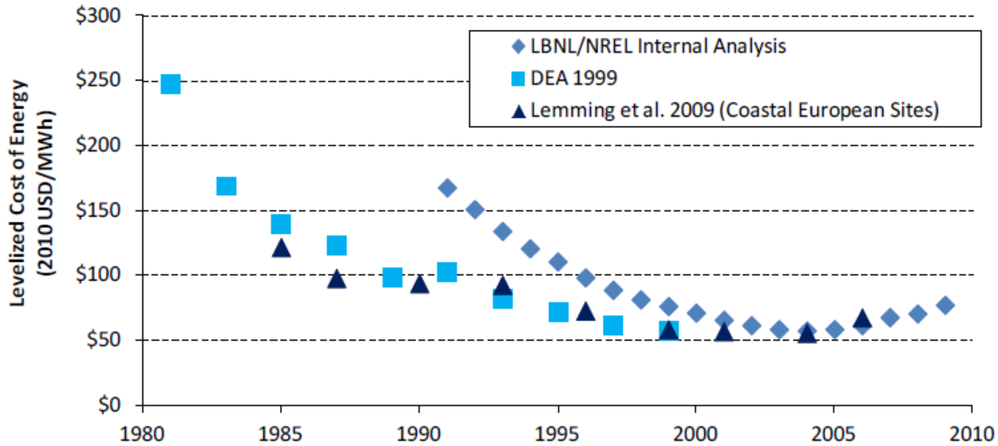


Figure 1. Estimated LCOE for wind energy in the United States and Europe 1980-2009 Source: National Renewable Energy Laboratory

Based on a longitudinal analysis of wind power in the future, the levelized cost is expected to decrease by 0-40% through the year 2030 (National Renewable Energy Laboratory, 2010). Of the studies analyzed by the NREL, those that estimate between a 35-45% decrease in the levelized cost represent scenarios that the NREL considers unrealistic (National Renewable Energy Laboratory, 2010). Figure 2 shows that the 20th to 80th percentile range of studies implies levelized cost reductions between 20 and 30% by the year 2030. Learning by doing and technological advancement, especially in the efficiency of drivetrain technology, are expected to help drive down the levelized cost, as could increasing competition between wind turbine manufacturers. However, the need to place wind power facilities in low wind speed sites could serve to drive up the levelized cost of electricity (National Renewable Energy Laboratory, 2010).

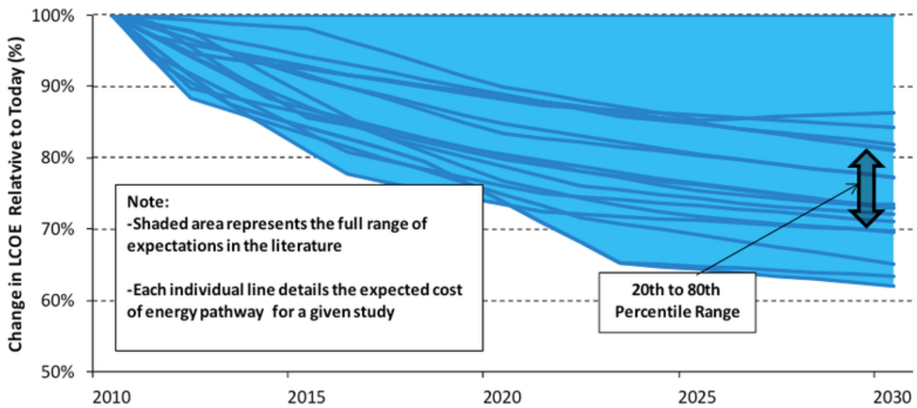


Figure 2. Projected levelized cost of electricity of wind power Source: National Renewable Energy Laboratory (2011)

1.3.2. Solar Photovoltaic (PV)

Solar PV cells utilize crystalline silicon panels and semiconductor devices to convert solar radiation into useful electricity by way of a power inverter and conditioner system. Groups of solar PV cells are configured in arrays or modules which can be used to charge batteries, operate motors, and to power any number of electrical loads based on the supply requirements that are designed into the system (Florida Solar Energy Center, 2007). The most efficient solar PV technologies currently available are able to convert 15% of the total solar radiation energy potential they receive into useful electricity (Murphy, 2011).

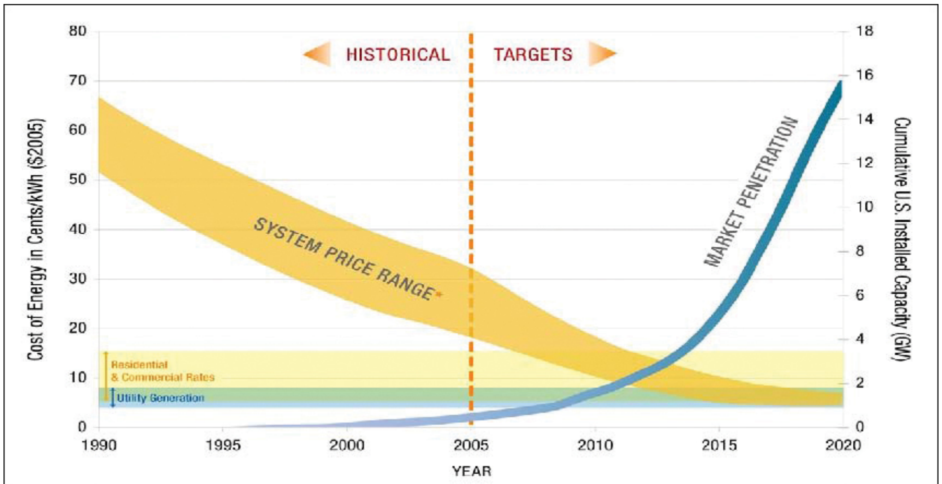
One of the key dimensions in assessing the viability of solar PV is siting requirements inherent to the technology. Solar PV modules and arrays must be situated in areas which receive sufficient solar radiation for the project to be commercially feasible (Murphy, 2012). Seasonal variation in sunlight is a significant factor in determining the commercial viability of solar PV installations (National Renewable Energy Laboratory, 1994).

As of September 2012, there is 17GW of total installed solar PV capacity worldwide (Reichelstein, 2012). The IEA estimates the levelized system cost of electricity for solar PV systems constructed in 2017 to be $152/MWh (see Table 1).

Work conducted by Richelstein (2012) at Stanford has concluded that cost efficiency gains have followed the traditional "80% learning by doing" curves[3] over the past 30 years and that learning by doing trends over the next decade will conform to past results. In terms of utility generation, there exist some – but not many – sites in the United States where solar installations are cost competitive with fossil fuel generation (Richelstein, 2012). For commercial generation Richelstein (2012) has found that in locations in the United States favourable to the solar radiation requirements, such as businesses with rooftop space for solar installation, solar PV is already cost competitive with fossil fuel fired methods of electricity generation.

In terms of utility scale generation (in excess of 1MW total installed capacity), Reichelsten estimates that levelized costs for solar are currently 35%-50% higher than competing fossil fuel fired methods (Reichelstein, 2012). In remote areas where transmission costs are very high, Richelstein (2012) has found that solar PV utility scale generation could become competitive with fossil fuel fired methods of generation by 2020. However, these results are dependent on existing tax subsidies for solar PV installations (Reichelstein, 2012). In other words, Richelstein's study is really discussing the potential for government regulation and incentive programs to subsidize a particular technology to the point where it can be cost competitive with other technologies.

[3] Citing Swanson (2006), Reichelstein observes that each time the cumulative installed capacity of solar panels has doubled (on a global scale) the prices of solar panels have fallen by an average of 20% (Reichelstein, 2012).



Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Figure 3. Levelized cost of electricity for solar PV, historical and projected
Source: Texas State Energy Conservation Office (2005)

The levelized cost of electricity from solar PV has decreased from $1.25/kWh in 1980 (in 2005 US dollars) to between $0.20/kWh and $0.30/kWh in 2006 (Texas State Energy Conservation Office, 2005). The Texas State Energy Conservation Office is a state level office under the authority of the Texas comptroller of public accounts tasked with maximizing energy efficiency while protecting the environment (Texas State Energy Conservation Office, 2013). Figure 3 is taken from an analysis conducted in 2005. It shows the current price ranges for system installation and operation converted into a levelized cost of electricity band. This figure reflects the state level policy environment where solar PV installations still receive substantial tax credits of 30% of the total capital installed costs in the United States, and the literature suggests that such tax credits will have to remain in place to ensure that learning curve rates of cost reductions remain uniform over the next 30 years.

1.3.3. Solar Thermal

Typical thermal solar generation installations concentrate solar radiation in flat or curved collectors and then reflect the solar radiation captured to heat a fluid. This heated fluid may be used for residential or industrial heating. Alternatively, it may be used to boil water, create steam and drive a turbine generator that produces electricity (Clean

Energy, 2009). The oldest technology is a parabolic trough. Curved parabolic plates are used to heat a solution that runs in pipes located at the focal point of the parabola. Power tower technology utilizes reflective parabolic troughs and flat mirrors to reflect the energy onto a tower in which a solution, typically molten salt, is then heated. Some sites may be more amenable to the installation of arrays of parabolic troughs, while others can take advantage of the gains afforded by power towers due to the physical topography of the site itself.

The cost of installing various types of concentrated solar power (CSP) systems is estimated by the IEA to be $242/MWh (see Table 1). This is nowhere near to being competitive with fossil fuel fired generation. Intermittency issues plague the viability of CSP for solar as well, and without viable utility scale storage mechanisms or the use of backup natural gas generators it is unlikely that they will be able to compete with fossil fuel fired generation in the near future.

1.3.4. Base vs. peak load

Demand for electricity can be divided into three major categories: base load, intermediate load, and peak load. Base load is defined as the minimum amount of electricity that a power producer must generate to meet the demand of its customers over a 24 hour period (Cordaro, 2008). Intermediate is variable but is defined as those demands placed on the power producer at predictable intervals such as in the early morning or the evening. Peak load is much harder to predict. It refers to loads arising under extreme climate conditions, such as cold snaps and heat waves. Global base load energy consumption is expected to increase by 36% from 2008 to 2035, rising from 143046.9 TWh to 194802.5 TWh (IEA, 2010). Base load power plants are defined by the International Energy Agency as power plants which have a capacity factor of 70% (they can operate for 70% of the 8760 hours in a year) (IEA, 2010). Base load power makes up the vast majority of electricity supply (EIA, 2012).

It has been argued that renewable energy technologies such as solar and wind do not have the technological and infrastructural capacity to serve as base load power generators. Fitzpatrick (2012) estimates the capacity factor for solar PV at 25%, thermal photovoltaic 18% and wind 34%, far below the accepted benchmark of 70%. Others argue that proponents of the fossil fuel industry, NIMBY (Not In My Backyard) and NAMBY (Not In Anyone's Back Yard) groups, and others are exaggerating the limitations of solar and wind to provide base load power (Canadian Renewable Energy Association, 2009; Diesendorf, 2010). The problem may be mitigated by the interconnection of geographically dispersed renewable energy generation facilities, the use of pumped storage mechanisms at geographically dispersed basins, and balancing supply with demand using integrated smart grid technology (Canadian Renewable Energy Association, 2009).

Stodola & Moday (2009) concluded that with investment in smart grid technology and high-voltage transmission, as outlined above, solar thermal and PV alone could account for a further 193 GW of total installed capacity in the United States, capable of operating at the 70% threshold delineated by the IEA, providing 7% of the total energy requirements of the United States. Further work conducted by the German Renewable Energies Agency found that, with attendant smart grid integration, solar and wind can provide base load power during the phasing out of conventional Generation II nuclear plants in Germany (Schmidt, 2010). However, this analysis has come under criticism for several reasons. A complete transition to renewables in Germany following the complete phase-out of nuclear power generation is estimated to cost over €250 billion over the next decade (Neubacher, 2011). That is in addition to the €13 billion a year provided by the German government in subsidy to renewable energy installation (Neubacher, 2011). The costs of a total switch to renewables are also accompanied with the German necessity to import nuclear power from neighbouring France and the Czech Republic (Neubacher, 2011). Since their decision to switch to renewables, Germany has been forced to import one quarter of its electricity previously generated domestically by nuclear power at significantly higher than nuclear-generated costs (Gitschier & Neubacher, 2011).

In terms of wind, it has been proposed that compressed air energy storage (CAES) be utilized to store excess energy generated by wind farms in geographically dispersed regions (Mason & Archer, 2012). CAES is a form of energy storage in which potential kinetic energy generated is stored in the form of pressurized air in underground facilities (Mason & Archer, 2012). CAES is a proven technology but it has efficiency losses of 50-70% (Mason & Archer, 2012). Another option proposed is a combination of wind farms and natural gas fired cogeneration plants with in-situ carbon capture and liquefaction mechanisms (Mason & Archer, 2012). In periods where wind power capacity falls below the 70% capacity factor of a typical 400MW generation facility, natural gas fired plants are then ramped online in as little as 10 minutes to make up for the shortfall (Mason & Archer, 2012). While not an ideal solution, the greenhouse gas emissions from such facilities, with in-site carbon capture mechanisms that liquefy the CO2 for later commercial use, are minimal (Mason & Archer, 2012).

While CAES may allow wind to be considered base load, it remains very expensive. A case study in Texas found that the levelized cost of electricity per kWh from wind with CAES can compete with CCGT technology at a carbon price of $56/tonne of CO2 and natural gas at $15/MMBTU, but that it requires a CO2 price of $236/tonne if natural gas was priced at $5/MMBTU (Fertig & Apt, 2011). At the time of writing (in 2013), natural gas costs $3.56/MMBTU. In the past four years the price of natural gas has declined dramatically, from a high of $15/MMBTU in early 2008, to the present low (Investment Mine, 2013). Other analyses show that if base load power from CAES wind is sold on the spot market alone, the investments become highly risky for power producers (Lund & Salagi, 2009).

1.4. Geothermal Energy

Geothermal energy is the harnessing of the heat generated in the earth's molten core and dissipated through its crust. Mankind has been harnessing geothermal energy since antiquity, typically in the form of thermal pools and hot springs utilized for heating, cooking and therapeutic purposes. The first engineered geothermal system was implemented in the 14th century in France in the form of a district heating system (Johnston, Narsilio, & Colls, 2011).

Due to the upfront capital costs that are several orders of magnitude higher than fossil fuel fired generation, geothermal energy is not at present economically competitive (Johnston, Narsilio, & Colls, 2011). As shown in Table 1, the most advanced heat pump technology available at this time produces levelized costs of electricity 50% higher than fossil fuel fired electricity generation, with upper bounds of the levelized cost of geothermal energy being estimated at $112/MWh. The materials used in deep bore geothermal heat sinks cannot be guaranteed to survive intact for timeframes comparable with the lifecycle of conventional power plants (Johnston, Narsilio, & Colls, 2011).

There is also the very real problem of slow heat dispersion in the earth's crust. Productivity of a particular geothermal energy source may decline over time. Constant drilling in geothermal active areas may be necessary to ensure a reliable source of geothermal energy supply (Murphy, 2012). Recirculating engineered geothermal systems are currently being explored to address the problem of heat dispersion. Materials science research is taking place to develop nanomaterial ceramics that can withstand the harsh environments inherent to geothermal power production. However, projections for commercialization of these technologies run even further than the 2050 introduction horizon for nuclear fusion demonstration reactors (Johnston, Narsilio, & Colls, 2011). It is estimated that even if every potential geothermal resource on earth were developed, factoring in efficiency losses, geothermal energy has a maximum potential for 2TW of total installed capacity (Murphy, 2012).

1.5. Nuclear Fission

Nuclear fission development has stalled in Western industrialized nations since the late 1970s (Ahearne, 2011). Investors are reluctant to pursue new nuclear construction for several reasons. First, the very high capital costs involved in constructing large scale base load nuclear power plants in the 1-3 GW range often lead investors to refuse to pursue these investments without significant government loan guarantees and subsidies (Dittmar, 2012; Holt, 2010). The high costs of decommissioning large scale nuclear power plants have also been cited by investors as a disincentive (Dittmar, 2012; Holt, 2010). There is also the dismal track record of astronomical cost overruns for experimental or non-standardized reactor designs (Dittmar, 2012; Holt, 2010). Siting concerns related to seismic uncertainty, the high level of public anxiety surrounding the potential for a nuclear accident, and questions as to future uranium supply have made the prospect of large scale new nuclear construction difficult for Western industrialized nations to pursue in non-command economies (OECD, 2004, 2008).

1.5.1. *Global Uranium Supply*

It is estimated that there is 5.3 million tonnes of known recoverable uranium ore on the planet which can be processed into nuclear fuel (World Nuclear Association, 2012). There are two varieties of natural uranium. U^{235} is the isotope of uranium which is 'fissile', in that it can be burned as fuel in a nuclear reactor following a process of enrichment (Murphy, 2012). U^{238} has the potential to be 'bred' into U^{239} which, after a period of just over 72 hours, undergoes two stages of radioactive decay which transmutes it into Pu^{239}, another fissile material which can be isolated for the production of nuclear weapons (Murphy, 2012). Of these two types of uranium, 99.3% of the uranium found on earth is of the U^{238} variety, with just 0.7% U^{235} (Murphy, 2012; World Nuclear Association, 2012). At current rates of uranium consumption for the generation of electricity (60,000 tonnes per year to generate 0.75 TWh per year, or 6% of global energy demand), with no further exploration taking place and assuming that all reserves of uranium are known, the current global uranium supply would be sufficient for 80 years (Murphy, 2012). Breeder reactors designed to transmute U^{238} into U^{239} which then decays into Pu^{239} have the potential to increase this available supply by a factor of 140, not taking into account the potential for thorium breeder reactors (Murphy, 2012). The introduction of breeder reactors increases the 80 year timescale into a millennium (Murphy, 2012).

The three meltdowns at Fukushima Dai-Ichi have brought future plans for nuclear expansion in major energy consuming countries under further scrutiny (Srinivasan, 2013; Nelson, 2012). While new nuclear construction around the globe has stalled, the development of advanced reactor designs has moved apace, laying the groundwork for future generations of reactors that can potentially address the major fuel supply concerns outlined above (Busby, 2009; Cleveland, 2005).

1.5.2. *Reactor Categories*

Nuclear reactors are typically referred to as Generations I through IV. Generation I plants were the first experimental pile reactors, of which none are still in operation (Mez, 2012). Generation II plants make up the vast majority of the operating global nuclear capacity, typified by various methods of heat generation using nuclear fuel, and utilizing vastly different coolant and energy capture mechanisms (Busby, 2009). Generation III and III+ reactor designs will make up the majority of new nuclear deployed over the next 20 years (Dittmar, 2012; Holt, 2010). Generation III and III+ reactors can be split into two categories. The first is traditional large scale (>1GW) generating capacity with modular designs and components combined with passive safety systems, which mitigates the need for backup power generation in the event of a coolant incident (Hyde, 2008; Kessides, 2012). The other is small modular 10-150MW capacity designs that utilize underground storage (Vujic, 2012). These are intended to provide power for remote regions traditionally dependent on fossil fuel fired methods of generation and for energy-intensive industrial development not situated near major power infrastructure (Vujic, 2012). Generation IV reactors are not expected to be deployed at the commercial scale before 2030, but proof of concept breeder reactors have been built and operated, most notably the SuperFenix breeder reactor in France, and demonstration reactors in Germany, India, and Japan (Jagannathan, 2006; Kessides, 2012; Lafuente, 2010; Pasztor, 1991). These reactors utilize novel mixtures of nuclear fuel for the intent of breeding nuclear fuel ad infinitum from readily available nuclear waste, which is reprocessed into burnable fuel, mitigating uranium scarcity concerns (Permana, 2008).

Generation III and III+ reactors may have a high potential to be economically competitive with fossil fuel fired methods of heat and electricity generation even without carbon pricing regimes (Pasztor, 1991; Kessides, 2010). According to the Energy Information Administration and the International Energy Agency (see Table 1), the levelized cost of electricity from advanced Generation III and III+ reactors is $111/MWh, roughly twice the levelized cost of natural gas without carbon capture and storage. Generation III and III+ differ from Generation II nuclear reactors in several attractive ways (Akorede, 2012; Apikyan, 2010; Busby, 2009; Cleveland, 2005). One key difference is the modular design and construction of such plants. Historically, nuclear power plants were site-specific designs constructed on the basis of military demands for fissile material that could be used for nuclear weapons programs (OECD 2008; OECD 2004). As a result, electricity generated was a convenient economic and social spinoff of weapons development (Pasztor, 1991). This scenario precluded the rollout of modular designs.

The modular designs reduce accident risk arising from system complexity, and reduce the capital costs associated with nuclear plant construction (Vujic, 2012). Generation III+ small modular reactors offer simpler, standardized, and safer modular design by being factory built, requiring smaller initial capital investment, and shorter construction times. They could be used in isolated locations without advanced infrastructure and without power grid, or could be clustered in a single site to provide a multi-module, large capacity power plant (Vujic, 2012).

The EIA and IEA reports provide levelized cost of electricity values only for the Westinghouse AP1000 Generation III and III+ designs as well as Small Modular Reactor Designs (See Table 1). A study conducted by the Canadian Energy Research Institute for the Canadian Nuclear Association in 2004 came to markedly different conclusions as to the levelized cost of advanced nuclear in reference to the CANDU-6 and CANDU ACR-700 Generation III and III+ reactor designs.[4]

In the 2004 study analyzing potential options for base load electricity generation in Ontario, CERI used two base assumptions for the construction of new nuclear power plants beginning in the early 2010s: the plants would be constructed on either a public or "merchant" basis. Merchant plants are constructed and operated by private investors. Public plants refer to a scenario in which the projects are not subject to income taxes or to the cost of financing through market debt or equity. With a 7% real discount rate, the CERI study found that on a merchant basis the levelized cost of electricity for an ACR-700 (and by extension, an ACR-1000) plant would be $83.66 (with a potential for the CANDU-6 LCOE to reach as high as $100 due to its older containment system) (CERI, 2004). On a public basis the study found that the levelized cost of electricity from both the ACR-700 and the CANDU-6 designs would range from $57/MWh to $66/MWh, with the ACR-700 design having the lowest cost fluctuations in the sensitivity analysis (CERI, 2004). At present natural gas prices, the ACR-700 is economically competitive with natural gas fired methods of electricity and heat generation without a carbon price.

[4] The Canadian Energy Research Institute defines itself as an independent, non-profit research establishment that has been providing objective, evidence based research on energy issues through a partnership of industry, academia, and government since 1975 (CERI, 2013). Its directors include business and government executives, plus some academics.

A key difference and advantage of Generation III and III+ reactors is the implementation of passive safety systems. Passive safety systems preclude the need for backup AC or DC generators which run off diesel fuel or natural gas to continue pumping coolant into the reactor in the event of a loss of coolant incident (Cummins, Corletti, & Schulz, 2003). Instead, a large pool of water is built into the reactor containment vessel which, in the event of a loss of coolant incident or the rupture of a coolant transmission line, uses the natural convection of water by heat generated by the reactor core to recirculate coolant (Cummins, Corletti, & Schulz, 2003). Generation III and III+ reactor designs which have already passed regulatory approval include the Westinghouse AP1000.

At the time of writing it remains to be established whether SMRs are economically competitive with natural gas fired generation. A multiple account cost benefit analysis of the Toshiba 4S reactor compared to a natural gas cogeneration facility for oil extraction in the oilsands conducted by Lutener, Domareski, and Ireson in 2012 found that only at carbon prices of $86/ton of CO2 would the Toshiba 4S become economically competitive with natural gas (Domareski, Ireson, & Lutener, 2012). This result is not consistent with the industry promotional literature which claims economic parity with natural gas (Kessides, 2010; Hyde, 2008).

Generation IV reactors utilize advanced cooling methods and core configurations to breed fissile material from spent nuclear fuel, high level radioactive waste, and transmutable materials that can be converted into fissile material (van Heek, 2011). These reactors span the gas-cooled, liquid metal cooled, and sodium cooled varieties, as well as thorium breeder and liquid fluoride breeder technologies (Anonymous, 1999). With the exception of thorium transmutable reactors, of the consensus in the literature is that Generation IV reactors could become economically competitive with fossil fuel fired generation by 2030 by virtue of their ability to utilize previously unsuitable fissile materials from the vast stockpiles of spent nuclear fuel currently sited in dry casks or liquid cooling pools at nuclear facilities across the globe (Mez, Lutz, 2012; Lafuente, 2010; Ahearne, 2011).

There is significant debate on the economics and physics of thorium reactors. Some conclude that thorium reactors will not be able to achieve safety requirements, and that thorium breeding prospects outlined in some of the scientific literature are overly optimistic (Nelson, 2012). Others argue that a thorium fuel cycle is an inherently attractive route to pursue as the material to be transmuted is multiple orders of magnitude higher in global availability than traditional uranium reserves (Jagannathan, 2006).

1.6. Thermonuclear Fusion

Fusion has been derided for ‘being 30 years away, forever’. Thermonuclear fusion is the opposite of fission: two atomic nuclei are fused together utilizing an apparatus which generates neutrons. The neutrons are captured in the form of heat energy (Hamacher, 2001). The process by which thermonuclear fusion is achieved utilizes deuterium, a radioactive isotope readily found in seawater, and tritium, a radioactive isotope which is a by-product of the fusion process itself which can then be captured to be used as fuel for future reactions (Stacey, 2010). Thermonuclear fusion generates no high level radioactive waste, and its low level radioactive waste remains radioactive for fewer than 125 years (Stacey, 2010).

1.6.1. Types of Fusion Technology

There are three major approaches accepted in the scientific literature to harness fusion energy for the production of electricity: magnetic confinement fusion (MCF), inertial confinement fusion (ICF), and magnetized target fusion (MTF). Magnetic confinement fusion is the process by which high temperature plasmas are contained in a magnetic field and then compressed to temperatures and pressures which exist on the surface of the sun (Ward, 2001). Inertial confinement fusion is achieved by focusing hundreds of high powered lasers on a fusion fuel target and then compressing the target to conditions which result in a fusion reaction (Smith, 2005). Magnetized target fusion is a process by which magnetized plasma configurations are merged and then compressed using a metal liner (Laberge, 2008).

Magnetic Confinement Fusion

Magnetic confinement fusion has received the largest share of research funding, and is the approach utilized by the multinational ITER consortium, which hopes to achieve 'ignition', where a self-perpetuating burning plasma will produce 'net-gain' energy, 10 times as much energy output as energy input (Ward, 2001). Figure 4 shows the progress made toward the self sustaining condition of 'ignition'. The expected cost of the ITER project is $20B USD, and will not generate any electricity. It is expected to attain these conditions by 2027, with a demonstration reactor being constructed by 2050.

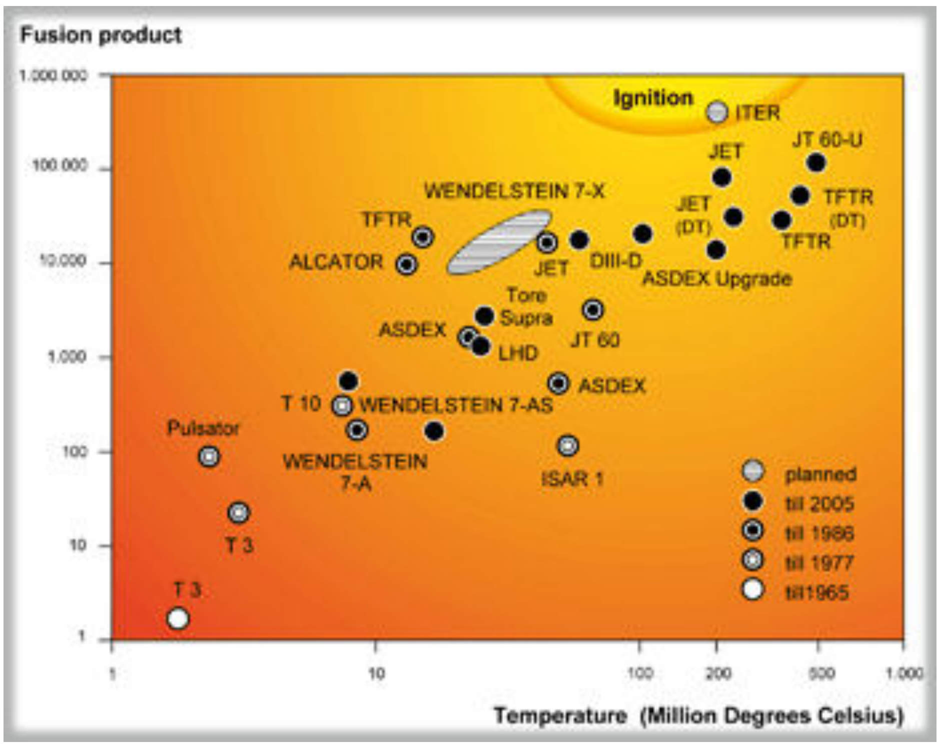


Figure 4. Progress of Magnetic Confinement Fusion – Y-Axis is Fusion energy product/X-axis is temperature in millions of degrees Celsius Source: University of Leipzig (2008)

The European Fusion Development Agency is responsible for the construction of ITER, as well as the socio-economic modelling of the potential impact of the introduction of commercialized fusion energy into the global market (EFDA, 2012). EFDA has been conducting extensive modelling exercises on the impact that fusion will have, and has assumed introduction of commercial fusion reactors by 2050, with fusion generating 36% of base load electricity by 2100 (EFDA, 2012). The results of the model on a global scale are shown in Figure 5. However, these demonstration and initial reactors using MCF will not be immediately economically competitive with fossil fuel fired methods of heat and electricity generation. Given current levels of natural gas prices they will require very high carbon prices, in the $150-$200/tonne range, to match levelized costs of fossil-fuel generation (Ward, 2001).

Work conducted by Marc Jaccard and Associates determined that carbon prices of $200/tonne will be required for Canada to meet its greenhouse gas emission targets by 2020 (MK Jaccard and Associates, 2009). Should ITER achieve its expected level of performance, following the construction of the prototype DEMO reactor in 2050, fusion could have a promising role in the future energy mix.

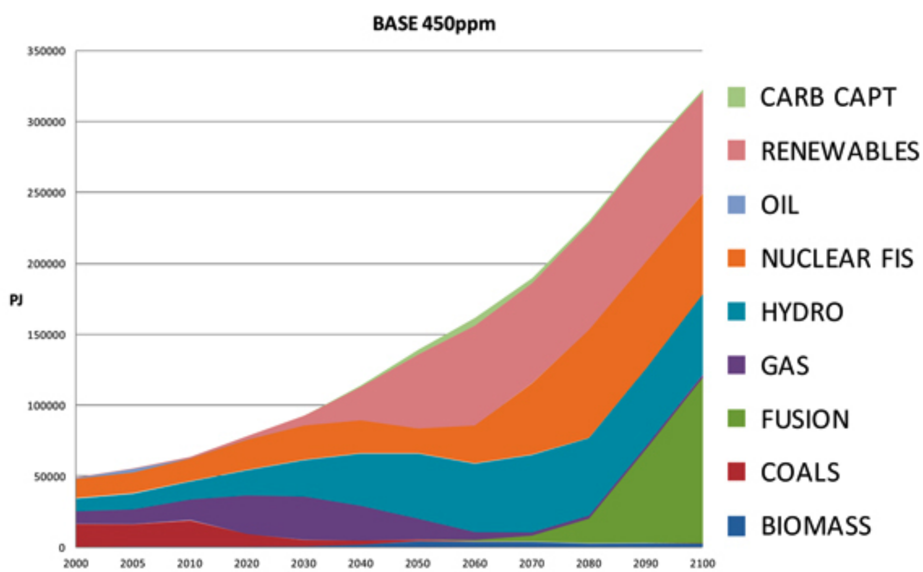


Figure 5. ***EFDA-TIMES Global Model 450ppm base case Source: European Fusion Development Agency***

Inertial Confinement Fusion

Inertial confinement fusion is a method developed to ensure the viability of the United States' nuclear arsenal without the need for costly or politically sensitive nuclear tests that also has the potential to achieve net gain energy production (Dean, S. O.

2003). It is a process by which high powered lasers are used to impact a spherical deuterium tritium gas pellet contained into a small cylindrical apparatus called a hohlraum. This apparatus focuses the laser energy in such a way that causes the deuterium and tritium atoms to fuse and produce heat generating neutrons. In terms of the generation of electricity, these neutrons are captured by the containment apparatus and can be converted into electricity through a variety of methods (Dean, S. O., 2003). At present, there is only one facility in the world capable of potentially reaching the threshold required for net gain that could then be commercialized, the National Ignition Facility in the United States. While it is expected to achieve net energy gain within the decade, it is unclear how the ICF concept could be then applied to commercial electricity production given that the construction of the prototype facility has cost $15B USD to date (Meier, W., 2002; Ward, D.J., 2001).

Magnetized Target Fusion

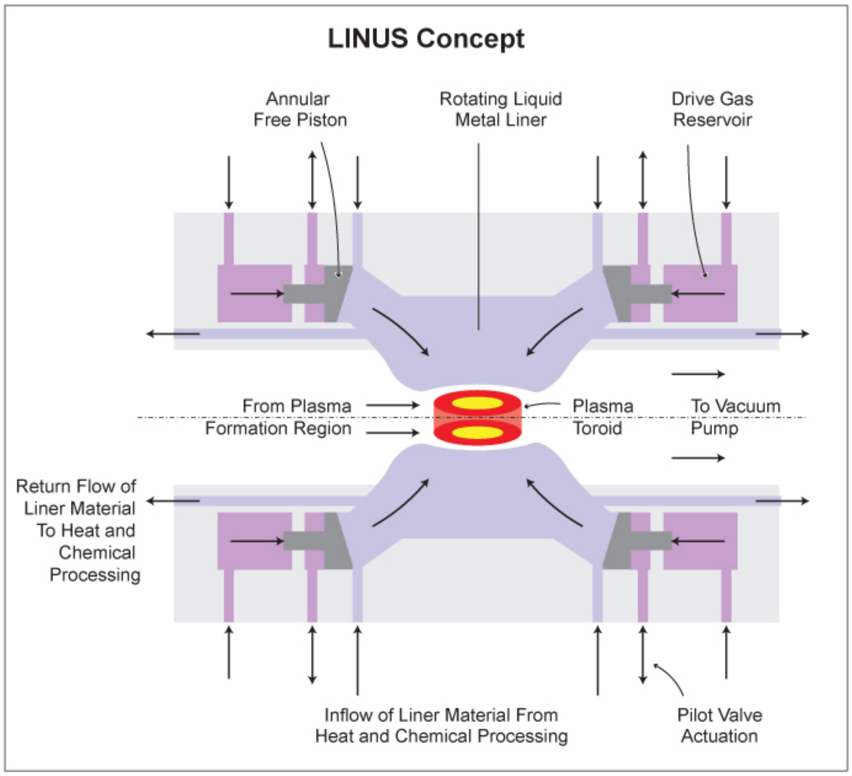


Figure 6. LINUS Magnetized Target Fusion Concept Source: General Fusion (2012)

Magnetized target fusion was first proposed in the 1970s but was not pursued as computational capabilities at the time were not sufficient to co-ordinate the compression of a metal liner using an explosive or acoustical mechanism (Miller, 2007). Figure 6 shows the rudimentary design of the original LINUS concept put forward by Los Alamos National Laboratories. It has the advantages of not requiring the long term development and implementation timescales of MCF (Laberge, 2008; Kirkpatrick, 1995). Unlike MCF there are no problems associated with tritium breeding blanket or materials design, nor do the problems of plasma impurity or the degradation of the reactor vessel exist given the inherent nature of the MTF concept (Ryutov, 2006). MTF does not require the construction of magnetic confinement plates, nor does it require the construction of a large cryostat (vacuum cooling vessel) (Robinson, 1999). There is significant consensus within the scientific literature that MTF is far more attractive, viable, and doable from a technical and economic point of view than MCF or ICF (Miller, 2007; Weston, 2010; Ward, 2001). At present several initiatives, both publicly and privately funded, are working on bringing MTF to the commercialization stage, with a prototype reactor expected to be built in 2022. Proof of concept experiments with MTF in both the private and public sectors have shown that MTF has a high neutron yield, and simulation work shows that the reactor designs being pursued operate well within the accepted and understood bounds of physics (Laberge, 2008; Kirkpatrick, 2007).

2. Methodology

The methodology includes a literature review of the technical and economic challenges facing various electricity generation technologies, and elite interviews. The interviewees were chosen as a result of their extensive experience and understanding of the various technologies, and for their activities as proponents, owner/operators, or representatives of companies and organizations that deal with these technologies on a daily basis. The interviews were conducted in person in the Lower Mainland region of British Columbia, or over the telephone where conditions required. The interviews were semi-structured, with a prepared interview script being sent to the interviewees by email prior to the interview.

The interviews began with an invitation for the interviewee to speak about the relevant technology in general. Following this preamble, a series of questions was asked of the interviewee relating to each specific technology. The questions typically began with queries about the levelized cost of electricity of various technologies, followed by questions about the various technological and social challenges inherent to the deployment of these various technologies. The interviewees were asked if their preferred technology has the capacity to generate base load electricity, if it emits greenhouse gasses (both during construction and operation), and if there are inherent challenges in grid integration.

Questions regarding economic efficiency gains due to technological advancement and learning by doing were asked about each technology, as were questions relating to the potential threat to public safety that each technology may pose. Interviewees were asked whether their preferred technology is already cost competitive with fossil fuel fired methods of generation, and if not, what they felt was the probability that it would become cost competitive within a thirty year time span. The interviewees were then asked what level of carbon price, if any, they felt would be required for their technology to become economically competitive with fossil fuel fired methods of electricity generation, in particular natural gas.

Specific questions as to the technical challenges of different technologies were asked for those technologies having a complex technical profile. Interviewees were encouraged to offer insights or thoughts beyond the limits of these questions, and at times their further comments served to inform more in-depth discussions regarding their preferred technology's place in the larger energy mix. The complete interview script is located in Appendix A.

3. Elite Interviews with Energy Experts and Stakeholders

The elite individuals interviewed, their positions, and their respective organizations are listed below:

Interviewee	Position	Organization
Anonymous Individual	CEO	Run of River Power Producer (Anonymized)
Michael Delage	VP Business Development	General Fusion
Ashley Derry	Operations Manager	BC Geothermal Energy Association
Craig Dunn	Head Engineer	Borealis Geopower
Nicholas Heap	BC Regional Director	Canadian Wind Energy Association
Martin Kennedy	Vice President	Capital Power Corporation
Nigel Protter	CEO & Executive Director	BC Sustainable Energy Association
John Stewart	Policy Director	Canadian Nuclear Association
Zoltan Tompa	Director of Partnerships	Sustainable Development Technology Canada

3.1. General Renewables: Nigel Protter – CEO and Executive Director of the BC Sustainable Energy Association

Protter is a proponent of run of river and large hydro. Investment in these technologies can ‘firm’ the electricity generated by intermittent sources of alternative generation such as wind and solar. He identified financial and technical risk in terms of wind and solar as a key reason that industry stakeholders are reticent to engage in the construction of new renewable projects. In terms of the technical barriers, Protter cited transmission efficiency losses as well as the high cost of building transmission infrastructure as a key barrier to the construction of renewable energy generation facilities at the utility scale. In many cases, even when an ideal site for renewables is found, the costs of building high voltage transmission to the project exceeds the net benefit of the project itself. Our civilization has invested very extensively in a hydrocarbon economy. This, he cited, is another reason why many of the major industry players are reluctant to engage in new renewable energy investments. Further, many existing hydrocarbon projects have yet to run their full life cycle and are still highly profitable for their owners and operators.

Speaking in broad strokes, he argued the lack of a level playing field is an explanation why renewable technologies, despite remarkable improvements in their cost competitiveness, have not seen significant market penetration. In other words, a key determinant for scaling up installation of alternatives is a carbon tax or carbon price via a cap and trade emissions permit scheme to a level at which natural gas fired methods of generation are no longer competitive with alternatives. As long as fossil fuel fired power generators are not compelled to account for the negative externalities inherent to their method of power generation, it will be impossible for any form of renewable energy to be cost competitive with fossil fuel fired methods of generation. When prompted to offer a suggestion of a carbon price or tax that would be sufficient for renewables to become competitive with fossil fuel fired generation, Protter was reluctant to provide exact figures. He pointed to studies conducted by Mark Jaccard and Associates that indicate that carbon prices would have to reach $200/tonne within a Canadian context (MK Jaccard and Associates, 2009). Another major concern is the lack of grid stability and aging infrastructure which has multiple problems of efficiency and load response.

In addition to economic cost considerations, he perceived opposition by individuals and communities as a key obstacle to the deployment of renewable energy generation technologies. There are very high levels of social and political opposition to the construction not only of wind and solar facilities, but also to the transmission infrastructure required to bring the electricity generated by these facilities to their end customers. Modern wind and solar face high levels of public opposition from citizens and environmental groups due to their perceived disruptive impact on the natural environment. This runs counter to the desires of many who live in potentially impacted communities and who want clean and cheap energy. Describing these attitudes as "perverse", he cited NIMBY dynamics as a key obstacle to the rollout of renewables in North America. He singled out BC as a jurisdiction in which such opposition is high. These dynamics persist despite much more stringent protocols than existed in former decades.

Protter estimated the present levelized cost of run of river hydroelectric generation for plants at utility scale (>10MW) to be 9-14 cents per kWh. In terms of wind, the present levelized cost was similar, but he concluded wind is not as profitable as run of river hydroelectric generation. However, his estimates for wind estimates run counter to the findings of the IEA and the NREL, with his lower estimate of 9 cents per kWh for wind being in line with that of the EIA. One explanation for why wind power is not as profitable in a British Columbian context as run of river hydro is the difference in the transmission and distribution costs between the two. Optimal onshore wind sites in British Columbia are typically located on mountain ranges which increase costs associated with transmission. Run of river hydro facilities, while possessing difficult geographical and geological profiles of their own are typically faced with lower transmission costs due to lower elevations. While wind has been a mature technology for 25-30 years, it is new in Canada and wind turbines have to be imported from the industry leaders such as the Dutch, and are only now beginning to be imported from new entrants into the market in India and China. His conclusion is that the load balancing and firming capability of wind cannot be guaranteed at a reasonable levelized cost to qualify wind as base load electricity. Such load balancing is contingent on the availability of pumped storage hydro mechanisms. Such mechanisms are already committed here in British Columbia. In terms of siting elsewhere in Canada such as Alberta, Saskatchewan and Manitoba there are opportunities for development. In sum, “hydro is reliably unreliable (due to season flow variation), while wind is unreliably unreliable.”

3.2. Wind: Nicholas Heap – CanWEA

According to Heap, the most significant obstacle to the widespread development of wind energy is its lack of economic competitiveness with the levelized cost of electricity from hydrocarbon fuel sources. Technological barriers no longer exist in terms of generating electricity from wind turbines. Speaking to the storage issue, he stated that pumped hydro storage is the only technically and economically feasible mechanism for wind to provide base load electricity. In areas with pre-existing hydro dam infrastructure, wind can provide 20% of total electricity demand within Canada by the year 2025. Referencing the success of Denmark (28% share of electricity generation from wind power), Spain (17-18%), North Dakota (22%) and PEI (20%), this is not a “stretch goal” in terms of feasibility (CanWEA, 2012). Based upon the work of the Canadian Wind Energy Association, it is completely feasible given current technology for a country such as Canada to provide 20% of its total electricity demand by wind power without performing any “major surgery” on the grid. It becomes more difficult to expand wind power once the 20% share is met, Heap acknowledged, and ultimately wind will only be a part of a total energy mix given pre-existing infrastructure investments and the geographic dispersion of appropriate pumped storage sites.

Table 2. Wind Turbine Speed Classifications Source: Vestas AG (2012)

Turbine Class	IEC I High Wind	IEC II Medium Wind	IEC III Low Wind
Annual average wind speed	10 m/s	8.5 m/s	7.5 m/s
Extreme 50-year gust	70 m/s	59.5 m/s	52.5 m/s
Turbulence classes	A 18%	A 18%	A 18%
	B 16%	B 16%	B 16%

A 20% reduction in the costs of wind energy has occurred within the past three to four years (CanWEA, 2012). Turbine manufacturers have rolled out designs specialized for different wind class sites. Table 2 shows the different classes of turbines and the wind speeds they are optimized for. Previously, wind turbine manufacturers were only manufacturing wind turbines optimized for ‘Class 1’ speeds, the highest wind speeds that can be harnessed using the technology. However, the majority of the world’s wind resources are Class II and III. As a result of turbine manufacturers offering turbines optimized for these wind classes, wind power producers are able to generate more electricity for a levelized cost of electricity that is 20% less than they were paying for Class I turbines. When optimized turbines are installed conforming to the wind profile, electricity generated increased by 20% and the turbines cost 20% less, which means that the average lifetime cost of a wind turbine has decreased by a third. However, it must be noted that the levelized costs put forward by CanWEA do not include substation construction costs to shunt the power across vast distances of power transmission (CanWEA, 2012; BC Hydro, 2007).

The post-subsidy levelized cost of electricity of wind varies in different jurisdictions according to local tax/subsidy policies. China and India offer significant government subsidies for wind power. BC is a more expensive jurisdiction in which to build wind energy than many others. The difficult topography of BC is a reason for this; remote sites relative to population centres is another. The majority of favourable wind sites are located in hard to reach areas such as mountain ranges and steep hillsides. BC as a whole requires 55,000 GWh of electricity a year to meet current demand (BC Hydro, 2007). At 20,000GWh of wind generated power a year, Heap estimated the levelized cost of wind power would be approximately $100/MWh. The (marginal) cost curve rises as you add more wind power to the system to a maximum levelized cost of electricity of $155/MWh as optimal sites are exhausted and transmission construction makes it much less competitive than other methods of generation. In areas with flat topography, such as Saskatchewan, the cost is much lower, approximately $81/MWh.

In the short term, the most significant obstacles to wind power achieving the 20% share CanWEA has set as a goal is an unwillingness on the part of utilities and the general public to meet rising electricity demand through the construction of new generation facilities. Referring in particular to BC, but stating that this is true for other regions as well, Heap stated that current electricity rates are too low at present to finance the refurbishment and replacement of aging infrastructure – whatever technology is chosen. BC is relying on aging generation and transmission infrastructure whose capital costs have long since been paid. It is his view that, in the long term, the high cost of replacement projects will ultimately favour the large scale deployment of wind power. The public and policy makers will ultimately see wind as a far more attractive alternative than the construction of new hydroelectricity projects. There is widespread public opposition to the construction of new hydro dams for a range of reasons, mainly stemming from environmental concerns and NIMBY and NAMBY opposition.

Significant advances in wind turbine technology occurred from the early 1980s to the present, whereby the cost of wind power installations, both onshore and offshore, have fallen by two thirds. An inadequate supply of wind turbines was cited as being responsible for price increases in the early 2000s coupled with rising demand from countries such as China, India, and the United States. Due to the global post-2008 recession, the price of wind turbines has begun to decline again, reflecting the advances that have come about by 'learning by doing' and improved efficiency of the technology. The entrance of new manufacturers from China and India was cited as another factor in these price declines, though in his opinion the turbines manufactured in China and India are not of the same quality as those manufactured in Denmark or the United States.

In Heap's opinion the probability of wind power becoming competitive with natural gas within the next 20 years is "100 percent". While acknowledging that the current low price of natural gas is disrupting predictions of cost competitiveness for wind made in the early 2000s, he cited the present inability of natural gas producers to export natural gas to the world market as an artificial deflator of domestic natural gas prices. In his view, the construction of LNG export facilities in North America will lead to natural gas prices matching more closely the energy-equivalent price of oil. Due to shale gas fracking in North America, natural gas prices are no longer adhering to price equivalence. In his view, oil has a price floor of $70 to $80 a barrel; therefore he does not see how a long term price of natural gas can be lower than $10 per MMbtu. He believes that provided natural gas reaches $10 per MMbtu wind power will be cost competitive with natural gas by the year 2032.

Heap acknowledged that there are GHG emissions associated with the construction of wind turbines. Ore must be mined from the ground and smelted into steel, and the process of constructing the turbine itself also creates emissions. Ultimately, the greenhouse gas coefficient of wind power is 12-18kg of GHGs per MWh.

Heap's preferred method of storage for providing base load electricity from wind power is pumped hydro storage because such facilities already exist in British Columbia and elsewhere. While taking care not to pick a favourite, he stated that different types of storage have niche uses but that the technology is not mature enough for them to be cost competitive with existing pumped hydro storage. While optimistic about the future potential for CAES, he pointed out that CAES also assumes a 100% natural gas backup to make up for intermittency and firming issues inherent to wind technology.

Speaking to the issue of policies necessary to make wind cost competitive with fossil fuel fired methods of generation in the short term, he advocated a combination of carbon prices and renewable portfolio standards. Citing work by the National Roundtable on the Environment and the Economy (National Roundtable on the Environment and the Economy, 2012) and studies by Marc Jaccard (MK Jaccard and Associates , 2009), in the medium to long term carbon prices would have to reach $200-$300 per tonne to make wind cost competitive with natural gas. Policy requirements such as renewable portfolio standards were more attractive to him in the short term. He stated that renewable portfolio standards in British Columbia have come about as a result of the public not viewing natural gas as a "clean" energy source. In his view, current carbon price of $30/tonne of CO2 equivalent is insufficient to compel fossil fuel fired generators to account for the negative externalities of their electricity production, but that carbon price increases to the range cited above will not happen overnight given political opposition. Therefore, renewable portfolio standards for new generation construction are his favoured policy mechanism for a 20% wind power target in various jurisdictions.

On the topic of risk to the environment and human health, stakeholder consultation and "social licence", the consent of community stakeholders and residents, are key to implementing wind power. Engaging in community outreach prior to the installation of wind farms in a meaningful, open, and transparent fashion is the most effective way to mitigate potential opposition. The key public concerns are the disruptive nature of the sound generated by wind turbines, their impact on the visual landscape, and the potential for bird kills. Evidence accrued through scientific study over the past thirty years counters claims of negative impacts on human health by wind power. When residents in communities where wind farms are proposed to be sited are presented with this evidence, the majority of community concerns are alleviated.

3.3. Run of River Small Hydro – Anonymous CEO of Independent Run of River Power Producer (Interviewee A)

In situ and in stream hydrokinetic technologies involve the use of underwater turbines that are anchored to a riverbed (Bibeau & Kassam, 2009). Run of river small hydro involves the construction of small dams that create traditional reservoirs which are then used to generate electricity through the release of water through a gravity well which drives a turbine. In situ and in stream turbine concepts cannot generate the amount of electricity required by utility companies. These technologies require "hundreds of times more machinery" than small hydro dams and turbines, with a much larger impact on the surrounding environment than conventional small hydro run of river installations. In stream and in situ installations are in no way cost competitive with other renewable technologies, and will not become so in the foreseeable future.

According to the CEO of this firm (Interviewee A), run of river hydro is not at present cost competitive with natural gas or other fossil fuel fired methods of electricity generation. Run of river small hydro cannot provide year-round base load power supply due to seasonal temperature variations and flow limitations. Interviewee A stated that at present run of river small hydro projects typically have a levelized cost of electricity between $100/MWh and $120/MWh.

Run of river power has predictable seasonal variation due to the fact that rivers in colder geographic locations freeze over the winter. There is also an unpredictable variation in the long term, as weather factors can lead to years in which flows through small hydro projects are much lower or higher than average. Investors are very cautious as to what annual electricity supply they can commit to provide to a larger utility.

Run of river small hydro production cannot become cost competitive with fossil fuel fired methods of generation without a carbon price of $120/tonne is Interviewee A's opinion. In addition to cost competitiveness, he cited the lack of cost-effective sites for potential deployment as a significant obstacle to widespread deployment of run of river small hydro. While there are 8,000 rivers in BC alone that have some potential for exploitation by off the shelf run of river technology, there are only about 200 rivers in which there is a potential for commercial deployment of small hydro technology.

Another key barrier to this technology is societal opposition to small hydro pumped storage facilities. There is a widespread public perception that independent power producers are subjecting rivers and streams to irreparable and significant damage. Given the stringent environmental monitoring and impact assessments that exist in Canada, Interviewee A insisted that the actual impact of small hydro run of river projects on micro-ecosystems surrounding streams is minimal.

Run of river small hydro is a proven and mature technology, but advances have been made in the past three decades to lower costs of construction. There is room for some further improvement, Interviewee A predicted, in the efficiency of bearings in turbines and streamlining the construction of these installations, but there will be no significant technological improvements in the foreseeable future.

As with wind, there are GHG emissions associated with the construction of run of river small hydro projects. The production of cement, the construction of turbines and the transportation of these components, as well as the construction of the facilities themselves result in GHG emissions. Interviewee A was unable to furnish a GHG coefficient per MWh of electricity produced, but pointed out there are no emissions associated with the actual generation of electricity.

Interviewee A cited demand management techniques and the implementation of smart grid technology as their preferred storage mechanism. These demand management techniques enable utilities to curtail the power supplied to a certain jurisdiction or customer at agreed upon times, or dramatically increase the price per KWh. Interviewee A stated that in their experience demand management techniques are the most viable mechanism available at present to act as a storage mechanism.

While Interviewee A believed that CAES was viable in specific locations where there is access to abandoned mines and geological sinks, it is highly expensive and will not be commercially competitive for many years to come.

3.4. Nuclear: John Stewart – Canadian Nuclear Association

Citing data gleaned from 50 years of nuclear electric power generation in Ontario, the current cost of nuclear power is 6.3 cents per kWh ($63/MWh). These cost figures are representative of the current Generation II CANDU fleet that makes up the vast majority of installed nuclear capacity in Canada. When asked about decommissioning costs of the plants at the end of their life cycle, Stewart explained that the cost of decommissioning is built into the cost of electricity sold onto the grid. This decommissioning cost also accounts for the storage of spent nuclear fuel, high and low level radioactive waste storage, and the costs associated with reclaiming land used for the siting of a nuclear power plant.

In terms of the potential for nuclear technology to mitigate GHG emissions, any nuclear technology, existing or proposed, has a very high potential to do so. Beyond the emissions associated with the construction of the plants themselves, which Stewart states are almost identical to those associated with comparably sized hydro or natural gas plant construction, nuclear power does not emit any GHGs. While the mining of uranium has emissions associated with its supply chain, the amount of GHGs created by uranium mining to power a nuclear power plant over a 60 year life cycle is ‘infinitesimal’, he insisted, compared to the GHG emissions associated with fossil fuel fired generation.

The advanced CANDU and CANDU-6 designs can be considered Generation III or III+ designs. Relative to Generation II reactors, they have much higher capacity factors, generate more electricity per unit of nuclear fuel, possess passive rather than active safety mechanisms, and produce less spent nuclear fuel to be stored. In Stewart’s opinion there are multiple niche markets in which it would not be feasible to construct large scale power plants but where small modular reactors (SMRs) could be used. They have “a high potential for deployment in Canada in remote regions” such as northern Alberta for the extraction of bitumen or for powering remote communities or desalinating water. Stewart reported a high interest in using SMRs to replace aging coal and natural gas facilities that are reaching the end of their life cycles. He sees a very strong probability of them being deployed in the future given the sound nature of the technology.

In regards to Generation IV nuclear technologies such as thorium and liquid fluoride reactors, Stewart said that it was too soon to prognosticate on their potential. The key message to take away from discussions regarding the role of nuclear in the future energy mix, summarized Stewart, is that there is a “flower bed” of options to be pursued, and that the potential for breeding fissile material and burning spent nuclear fuel is virtually unlimited. In his opinion nuclear holds multiple advantages over competing technologies such as hydroelectric generation, which is already limited by site specific constraints, and natural gas fired methods of power generation, which are not expected to see any transformational technical progress in the near or long term.

The slow rate of adoption of advanced CANDU and CANDU-6 designs, insists Stewart, is not due to the limitations of the technology, but to the projected slow growth of power demand. If Canada experiences slow economic growth over the next twenty years, then power producers will be waiting for old coal fired and natural gas fired plants to reach the end of their life cycle not investing in new nuclear capacity. Whether Generation III and III+ plants will be built is directly tied to Canadian economic growth rates.

Provincial government support for nuclear power according to Stewart is strongest in Ontario and Saskatchewan, with emerging support from the Alberta government for nuclear power in extracting bitumen from the oilsands. On the other hand, over the past two decades the federal government has disengaged. Private industry is very supportive of new nuclear construction due to the certainty it provides to electricity prices and to reliable base load electricity. Stewart noted that industry in Canada has a vested interest in nuclear power because of the sector’s innovation potential and because of business opportunities for Canadian firms.

Stewart does not believe that natural gas will remain at present low prices. Stewart argues that power producers building new natural gas plants are in effect taking a large gamble on extrapolating present natural gas prices. Should the price of natural gas double within the next 10 to 15 years, the variable costs of operating natural gas plants will essentially double as well. Stewart contrasts this situation to nuclear, where the price of uranium has been historically stable, with very little volatility. Furthermore, changes in the price of uranium only marginally impact the cost of nuclear fuel, the majority of such costs are incurred by the processing of uranium into nuclear fuel rods. The historical price of nuclear power generation is virtually unaffected by the price of uranium.

Stewart volunteered two means of improving public perceptions of nuclear power – one “glib” and one “serious”. His glib tactic was to “grind up its waste and blow it off into the atmosphere as our fossil-fuel competitors do.” His “serious” tactic was to raise public awareness on the limited health impacts of radiation and the prospect that used fuel can and will be used as a fuel in advanced designs. Calling spent nuclear fuel a “fuel for the future”, Stewart pointed out that spent nuclear fuel still has 99% of its potential energy waiting to be exploited.

The lives lost per MWh of electricity produced by nuclear power is essentially zero. The only exception is Chernobyl. The World Health Organization estimates the mortality stemming from it at 4,000 total cancer deaths on top of the firefighters and emergency personnel killed at the site of the accident. In comparison, Stewart points out that 4,000 is a conservative estimate of the number of Chinese workers killed each year mining and transporting coal. Speaking to the recent disaster at Fukushima, the only two people who died at Fukushima lost their lives as a result of drowning. Others were killed in the subsequent evacuation; others had to move, and many people panicked. However, Stewart states that not a single documented fatality from radioactive release at Fukushima has come to light and he does not expect there to be one. Speaking to the Three Mile Island Incident, there was no emission of radioactive gas recorded in the vicinity.

Nuclear does not require the implementation of a carbon price to become economically competitive with fossil fuel fired generation in Canada in Stewart’s opinion. Stewart insisted that off the shelf nuclear technology, as well as advanced technologies such as the advanced CANDU and CANDU-6, are already competitive with fossil fuel generation under existing carbon pricing regimes. In Stewart's analysis, carbon pricing would merely strengthen the already strong case for nuclear as means to reduce GHG emissions.

Stewart would not use the phrase 'learning by doing' in describing progress made through experience with complex procedures (such as the refurbishing of CANDU reactors at the 20 year milestone). The biggest advances made in such complex and expensive capital projects are advances in project management techniques. Looking to the future, Stewart stated that the move away from large scale 800MW-1GW reactors toward smaller reactor designs of a 125MW capacity would complicate assessment of the cost per MWh. Building smaller reactors drives up the cost of reactor construction, but not of operation. A smaller reactor will meet the needs of niche areas such as at military installations, resource extraction sites in remote areas, and the desalination of water for water supply. Given the wide diversity of potential near future developments, and an anticipated shift to thorium reactors once they come online, the uncertainties become too complex to provide any reliable forecasts.

3.5. Geothermal: Craig Dunn – Borealis Energy

The levelized cost of electricity from geothermal power depends on the heat reservoir specific to a particular geothermal power project. Levelized costs of electricity from geothermal in ideal geographical locations such as Iceland can be as low as $10/MWh due to the unique volcanic geological profile of that region. In more typical geological profiles (such as California). Dunn estimated the levelized cost of electricity for a geothermal power plant would be $70-$100/MWh for project development. He points out that the upfront capital costs for geothermal projects vary considerably given the site specific nature of the technology. For example, in northern Ontario, which does not have an ideal geologic profile for geothermal projects, the levelized cost of electricity for geothermal could be double or triple that in California.

Geothermal has a 95% base load capacity; nuclear and coal do not have capacity profiles as attractive. The resource being exploited by geothermal is a constant, steam drawn out from the earth or heat energy channelled from hot rocks in the earth's crust. Dunn acknowledged the problem of slow heat dispersion in sites exploited for geothermal. He drew the analogy of "too many straws in the milkshake." In his experience, the best way to achieve good stewardship of geothermal resources is to engage in meticulous modelling of heat reservoirs prior to the construction of a geothermal facility. In his words, "Simply put, you hire the best geoscientist you can… because if you run out of heat, you run out of power."

There are several barriers to the widespread deployment of geothermal power beyond site specific requirements. The first acknowledged was that of scale of project design. Small geothermal projects of the 5-10MW installed capacity scale are very difficult if not impossible to implement. A typical geothermal project will only be implemented if it is within the 20-50MW installed capacity range. Dunn cited the 20-50MW range as the most "cost effective and attractive" profile for investors.

Geothermal has very low operation and maintenance costs compared to other technologies. However, the upfront capital costs are significant in determining levelized unit costs. While a natural gas plant has up front costs as well, the fuel costs for operating such a plant are incurred over time as power is being generated and sold. Geothermal is the equivalent of constructing a natural gas plant and having to pay up front not only construction costs but (nearly) all operating costs as well. When asked about the up front capital costs of geothermal power projects, Dunn said once they are constructed the up front capital cost is typically $5-$10M per MW of installed capacity. This includes geologic exploration and heat reservoir modelling, the drilling of the holes to install the heat extraction coils, and the installation of the coils themselves. Dunn lamented that even with an attractive levelized cost of electricity profile these very high up front capital costs were a key obstacle in securing investor backing for geothermal projects.

Another key barrier to the widespread deployment of geothermal energy is the paucity of public knowledge about geothermal resources. There are very few people who can answer specific questions about the economics and risks in the technology. He described speaking about the benefits of geothermal to policy makers and individuals as a situation in which he would "be starting from less than scratch." This translates into a limited number of potential investors who in turn become an even smaller pool when they are confronted with the relatively high up front capital costs of such projects. While wind and solar technologies have high public awareness, the geothermal industry is in its infancy from a public awareness perspective.

Another significant barrier is a complete regulatory void, which in turn leads to no awareness or support at the policy maker level. With the exception of British Columbia, there is not a single province or territory in Canada that has a regulatory framework to grant a licence for the construction and operation of a geothermal power plant. Dunn pointed out that his company, Borealis Energy, is the only company that has pursued an application for a lease for geothermal electricity generation in a regulatory environment where such an application process does not exist. As for the BC regulatory environment, there are regulatory protocols in place, but they are centred around an oil and gas regulatory framework, which does not address the radically different geothermal construction and operation profiles. Framing the problem as a chicken and egg scenario, geothermal projects cannot be pushed forward in Canada if there is no policy framework, and if there are no projects being pushed forward, no policy framework will emerge.

Dunn cited the need for cutting drilling costs and reducing 'geologic risk' as the key technological barriers that geothermal needs to overcome before it can be suitable for widespread deployment. Dunn defined geologic risk as the uncertain heat supply in potential sites over the life of the project. The Canadian Geothermal Energy Association should categorize resource potential in terms of confidence of supply and project life. While it may seem obvious that 'geologic risk' would need to be presented to potential investors, the creation of a standardized code based on scientific evaluation is a relatively recent development in the geothermal generation industry. The Geothermal Energy Association has developed such a code and feel that it is an important step in establishing a broader framework for addressing uncertainty of supply concerns for investors. Second, high and uncertain drilling costs are another important technological barrier to promote the widespread deployment of geothermal technology. In many geothermal projects 40-70% of the upfront capital costs, are associated with drilling. If the industry can drill faster and cheaper and hit a productive reservoir, then geothermal improves in terms of its viability and economic success.

In specific areas in British Columbia Dunn believes geothermal is already cost competitive with natural gas – without any form of carbon tax. From a global perspective, geothermal is highly competitive with natural gas in some regions such as Japan, where the costs of natural gas are very high compared to North America. Not only the levelized cost of electricity needs to be taken into account to attract investors to geothermal, but also the short term payback enjoyed by natural gas compared to geothermal. Dunn qualified his estimates of cost competitiveness by saying that at a natural gas cost of $3.5/GJ over the next 20 years, geothermal will not be cost competitive, but close to being so.

When discussing learning by doing advances, Dunn stated that the geothermal industry is still decades behind the oil and gas industry in the development of advanced drill bits, pump technology and water technology. Once advances made in these areas can be adapted to the geothermal industry, geothermal development will accelerate globally. However, he concluded that the geothermal industry itself is not well positioned to take a leadership role in these adaptations given the enormous asymmetries in terms of research and development resources between the geothermal and oil and gas sectors. The real drivers that have improved the competitiveness of geothermal over time has been the shift towards monitoring the emissions of fossil fuel generation. Simply monitoring levels of greenhouse gas emissions has increased the wider public understanding of what characteristics future energy generation facilities should have. In Dunn's experience, when customers ask that a new generation project be clean and provide base load power, when they "do the math", they wind up contacting his company. His answer has always been, when customers do call, "yes".

Speaking to the scale of geothermal power plants, the larger the geothermal energy project the lower the ultimate levelized cost of electricity. Once the 10MW installed capacity threshold is met, construction costs begin to plateau and levelized costs decline. Once the 50MW threshold is met, the levelized cost of electricity plateaus and no further scaling gains can be achieved of any significance.

Lives lost per MWh generated by geothermal are insignificant in Dunn's words. Speaking to wider environmental risk of geothermal, he considered that the process of drilling poses the greatest hazard. However, geothermal has a "phenomenal" record in this regard, as geothermal drilling does not involve the extraction of a flammable and/or toxic resource from the earth. In terms of the facilities themselves, the superheated steam and fluids that run through the facility are the greatest safety issue. Superheated steam and fluids are the resource being extracted to ensure revenues. These materials are stringently monitored not only from a safety perspective, but from a business perspective.

Dunn concluded that there is a lot of opportunity for the industry to better model grid integration. The costs to transmit power from reservoirs with attractive heat potential may result in a negative net benefit for the entire project. Cataloguing the potential of geothermal sites situated near existing grid structures will increase the penetration of the technology.

3.6. Thermonuclear Fusion and Advanced Nuclear: Michael Delage – Vice President of Business Development / General Fusion

The most significant obstacle to the commercializing of General Fusion's magnetized target fusion (MTF) technology is playing catch up with the fundamental physics of magnetized target fusion. It is a less explored path than other approaches to achieving commercial fusion. It is unknown if toroidial plasma formations can be compressed by a liquid metal liner and retain stability long enough for net gain conditions to be met. All simulation work done to this point by General Fusion, Los Alamos National laboratory, and other national laboratories and universities indicates that it is physically possible. However, given the highly complex instabilities inherent in driven plasma formations, it is impossible to ascertain whether or not these conditions to reach net gain are possible until a technical test is conducted and verified. General Fusion is in the process of preparing for such a test in the near future in line with their program to construct a prototype reactor by the end of the decade.

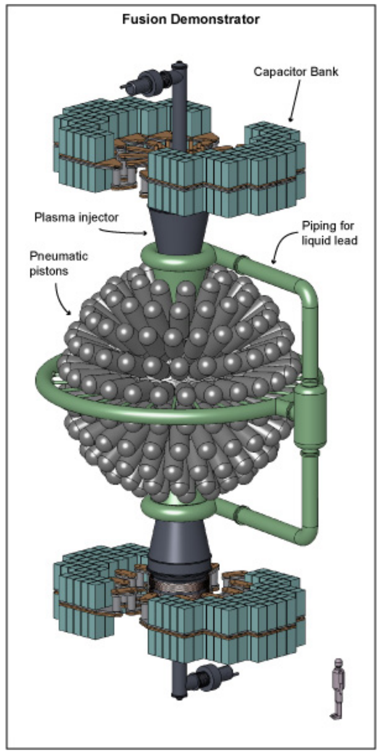


Figure 7. ***Magnetized Target Fusion Reactor Design Source: General Fusion (2012) Artist credit: Kris Holland***

Even if a prototype is successful, there are significant engineering obstacles inherent in constructing a commercially feasible reactor. Such problems include the construction of an extraction system to remove tritium from the liquid metal liner for use as fuel in reactions. Making an analogy to the history of manned flight, Delage stated that the first Wright brothers glider was not that useful from a commercial perspective. A period of 50 years had to elapse before motor driven gliders were adapted for commercial air transportation on a global scale. Delage expressed confidence that once the fundamental physics breakthrough is achieved, engineering obstacles such as tritium extraction will be surmounted.

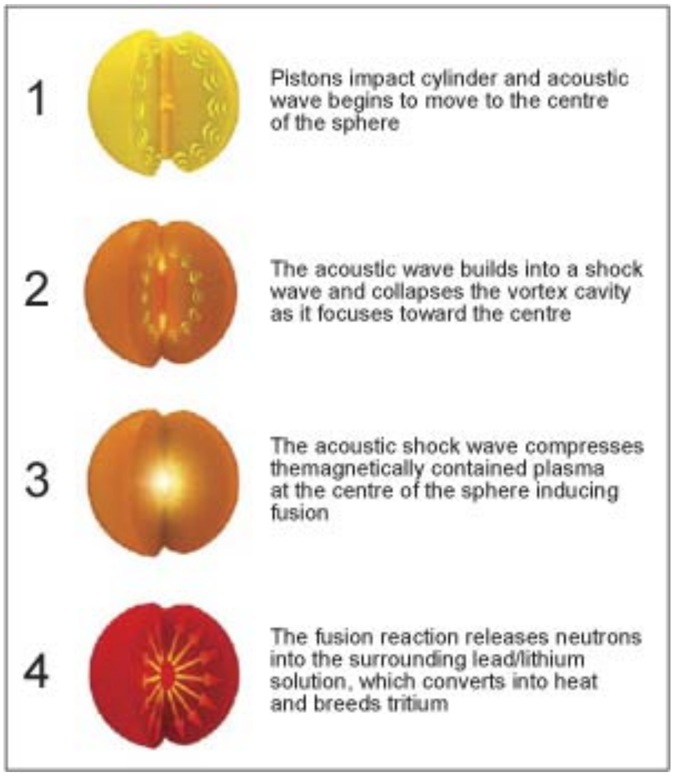


Figure 8. ***Energy capture principle of magnetized target fusion Source: General Fusion (2012)***

One advantage that magnetized target fusion has over magnetic confinement fusion is that the liquid liner takes the place of modular walls to contain and harness energy from the neutron flux generated by fusion reactions. As noted above, a significant obstacle to the commercialization of magnetic confinement fusion is the disruption of the atomic lattice of the containment and fuel generation system in a tokomak reactor ('Tokomak' is the Russian word for 'toroid', which is the geometric configuration of typical magnetic confinement fusion devices). This leads to parts of the wall having to be replaced at a significant cost. The liquid metal liner use in magnetized target fusion acts as the vehicle for the acoustic force that compresses the toroidial plasmas and generates the fusion reaction. By definition the liquid container cannot be damaged. A fusion power system that utilizes a liquid metal confinement wall will lead to much more rapid commercialization once the fundamental physics are proven.

The prototype reactor would be highly expensive, over $2B. Comparing it to the construction of the first commercial fission power plants, Delage described the costs of constructing the initial reactor as a combination of research and development and capital construction costs. Delage cited traditional technological learning curves of 20% efficiency gains for each doubling of capacity. Qualifying his cost estimate by acknowledging that it depends on adoption rates by governments and private industry, his view was that a levelized cost of electricity from a magnetized fusion plant of 100 MW capacity operating at 90% capacity would fall to $40/MWh within a decade of the first prototype being constructed.

Speaking to the issue of policy support for fusion research in general and magnetized fusion research in particular, Delage noted that Canada has not had a fusion program since the 1990s. There is no real government support for fusion technology in Canada. However, Delage explained that fusion research in Canada, and specifically General Fusion, has received funding from government financed clean technology sources, in particular Sustainable Development Technology Canada (SDTC). General Fusion has received a $14M grant from SDTC. Other private investors have financed the company to its present value of $50M. General Fusion's grant from SDTC is the largest that SDTC has made. According to Delage this grant has acted as a catalyst to open up discussions with key strategic partners for the potential deployment of General Fusion's technology. This is a result of both the size of the grant and the "respect" that a robust fund such as SDTC carries within the advanced energy generation investment community.

General Fusion's technology, once proven, will provide base load electricity with a 90% capacity factor. Delage pointed out that there will not be 100% uptime as the reactor will have to be shut down for periodic maintenance. As a base load energy source, magnetized target fusion has capacity factors similar to natural gas, nuclear fission, and coal. Magnetized target fusion technology will not emit GHGs during its operation. The only carbon footprint associated with the technology is from construction of the facility itself, and the transport of needed materials and workers to and from the plant. In terms of challenges relating to grid integration and infrastructure, the technology does not have any of the drawbacks associated with renewables, and also does not require the very large grids that gigawatt scale power plants require. With magnetized target fusion, you are potentially putting your footprint directly next to your customers. General Fusion's technology is also ideally suited for remote locations.

Once the plant is built, with the exception of deuterium that needs to be shipped in, the facility manufactures its own fuel through the process of generating fusion reactions.

The waste stream from General Fusion's magnetized target fusion technology has a much different profile from that of nuclear fission or other potential fusion approaches. The only by-product is helium gas. Beyond that, the only radioactive material that remains at the end of the life of a fusion facility is the low level radioactive waste in the pipes and metal structures used to contain the reactions. Delage compared the radioactive profile of these structures and substances to that of retired nuclear medicine technology, such as CAT scan machines. At the end of the life of a magnetized target fusion reactor it is expected that this low level radioactive waste, which takes the form of a dry solid, will be stored in a facility where it will take several decades to cool off to levels equal to typical background radiation. At that point the materials are safe enough to be melted down and recycled into other materials.

When asked the required level of carbon price to make General Fusion's magnetized target fusion technology economically competitive with natural gas, Delage estimated that, once the first and second prototypes are constructed, a carbon price of \$15-\$30 per tonne of CO2 would be sufficient. Targeted fusion technology would certainly not require carbon prices in the range of \$100-\$200, levels that other alternative energy sources require to ensure cost competitiveness with fossil fuel generation. If the price of natural gas rises to \$4.95 or \$6.30/MMbtu this would remove the need for any carbon price to ensure cost competitiveness. Speaking to a BC context, what affects the construction of generation in BC is not a carbon tax, but government policies that instruct power authorities to build new sources of generation that emit no greenhouse gasses.

Given the much lower research and development costs and the potential for much more rapid commercialization of magnetized target fusion compared to magnetic confinement fusion, Delage offered some insights as to why magnetized target fusion faces a 'developmental deficit'. It is the nature of science that expertise and funding will follow the most established approach to solving a problem, in this case fusion. Citing the breakthrough in tokomak design that occurred in the 1970s and the claims by many in the scientific community that the fundamental physics could be worked out in 20 years, a global race toward attaining fusion through magnetic confinement methods began. During this race, larger and larger tokomaks were constructed without the fundamental physics being explored sufficiently to determine if the construction programs would ever produce net energy gain.

More money followed the previous research dollars sucked into the programs, as did more funding for the training of scientists to explore magnetic confinement fusion. Twenty years later, Michel Laberge, the plasma physicist behind General Fusion's approach to magnetized target fusion came up with the idea to use steam actuated pistons. This has spurred a new interest on a global scale in the potential for magnetized target fusion to become a commercial source of fusion energy long before the expected construction of the first demonstration magnetized confinement reactor.

As to the fundamental viability of magnetized target fusion, Delage presented an overview of the government-sponsored and private endeavours to prove the physics of magnetized target fusion. First, Delage related the collaboration between General Fusion and Los Alamos National Laboratories in the United States and a similar project being undertaken by a Chinese national laboratory. Neither of them had received funding in excess of $30M USD. The Chinese project is still in its infancy and Los Alamos will undertake several experiments to prove the physics of magnetized target fusion beginning in 2014. A Russian project called MAGO (which is the Russian acronym for magnetized target fusion) has received intermittent funding for the past three decades, and there are indications that the effort has received an undisclosed amount of private financing.

At Sandia National Laboratories in the United States an effort (called MagLIF) is being undertaken to prove the fundamental physics of magnetized target fusion. Experiments at the Omega Laser Fusion Facility at the University of Rochester have also yielded increases in neutron yields of 30% over what has already been achieved at other national laboratories in the United States.

In terms of other efforts within the private sector to commercialize fusion power, Delage spoke of an entirely privately funded endeavour in the United States called Tri-Alpha Energy. The company is attempting to achieve commercial net gain fusion using a variant of magnetic confinement fusion without the central core configuration seen in tokomak designs (in which compact toroid plasmas are collided and contained using high power particle beams). While they may be viewed as the "competition" for General Fusion in the private sector, Delage took pains to state that when it comes to achieving net gain fusion the real competition is Mother Nature, not other companies or scientific endeavours.

Given his extensive experience in working with potential strategic partners in the nuclear sector as well as his engineering science background, Delage was happy to offer his views on the viability of advanced reactor designs both existing and planned for their potential to mitigate greenhouse gas emissions in the future. Speaking to thorium breeder reactors, Delage is of the opinion that the science has been proven and the construction and operation of breeder reactors has already been accomplished by governments, citing the SuperFenix in France as well as projects in Germany in Japan. Speaking to the economic viability of thorium reactors, Delage was quick to point out that molten salt as a cooling mechanism has its own problems, such as the "brutally radioactive" nature of molten salt cooling systems for thorium breeding reactors. Acknowledging the "inherently safe" nature of the containment units developed thus far for thorium breeding reactors, Delage argued that it has also been proven that light water conventional uranium reactors can have passive safety systems built into them as well, citing the Westinghouse AP1000 and the CANDU ACR 700 as examples of designs approved by regulatory authorities in North America and elsewhere.

Stating that he is "one of those people that believes the risks of nuclear power are overstated", Delage pointed to the CANDU-6 and the CANDU ACR-700 reactor designs as his preferred Generation III+ technology. It is already in operation in locations around the world. These designs are "woefully under marketed and under promoted." He cited the fact that CANDU-6 reactors already have the inherent capability to burn natural uranium (a mixture of a very small amount of U^{235} and the rest being U^{238}, the key point being that the fuel does not need to be enriched in U^{235}, which is a very expensive process) and that efforts in China are already underway to modify CANDU-6 reactors to transmute thorium into fissile material for future burning. While there is only 100 years of fissile U^{235} left on the planet at present rates of consumption, at present it is still less expensive to build a light water reactor such as the CANDU-6 than it would be to build a Generation IV or III+ reactor based on traditional thorium breeding designs.

Speaking to the Generation IV design being pursued by TerraPower, a private company that has received massive funding from the private sector (most notably a $400M financing round from entrepreneur and philanthropist Bill Gates), Delage stated that TerraPower has abandoned their initial plans for a travelling wave reactor in favour of a modular fuel replacement breeding reactor that will use depleted uranium as fuel. Optimistic about the potential for such a design to be commercialized, Delage stated that their construction timelines to build a demonstration reactor by 2022 were realistic and that there are no inherent physics or engineering obstacles to derail the commercialization of such a design. Advantages of the TWP-R design being promoted by TerraPower include keeping the coolant at atmospheric pressure as opposed to high pressures, the zero probability of a loss of coolant accident given the design of the reactor itself, its reliance on natural air circulation as opposed to diesel powered pumps for decay heat removal, and the fact that the nuclear reactions do not generate flammable hydrogen gas. Delage spoke to the favourable economics of TerraPower's design, stating that the concept eliminates the need for costly fuel enrichment, fuel reprocessing, burns nuclear waste as fuel, and does not require refuelling until the core is exhausted in 40 years time. All of these advantages indicate that the Generation IV design being pursued by TerraPower will have highly significant cost advantages to Generation III and III+ reactors as they completely alter the assumptions of previous economic analyses of the economic competitiveness of traditional reactors.

When asked what are the most significant obstacles to new nuclear capacity at present, Delage stated that one reason is that reactor construction has become very expensive. The supply chain that was feeding components into reactor construction during the last period of significant new nuclear construction in the 1970s no longer exists. If new nuclear construction is to be ordered, entirely new production lines are required to make specific components for use in nuclear construction. Delage also spoke to a significant skills shortage of individuals with experience in the construction of nuclear reactors.

3.7. Natural Gas: Martin Kennedy – Vice President Capital Power Corporation

Kennedy opened the discussion by discussing the major reversal in the role of natural gas in the global energy mix within the last three years. Previously the focus of the power industry was on the perceived scarcity of natural gas and high natural gas prices. Another major focus was on the volatility of natural gas prices, a volatility that for a time eliminated natural gas from consideration as a suitable fuel for base load power generation. Due to technological advances in drilling and exploitation, power companies now see natural gas as the most attractive fuel for base load generation. The reversal has been so significant that the availability of such a low cost fuel has repatriated manufacturing investments to the United States from abroad. Other effects of this reversal have been the redesigning and repurposing of entire liquefied natural gas terminals for export as opposed to their initial design specification for import.

Citing numerous projections made by industry, academia, and his own company, Kennedy believes natural gas prices will remain below $5/MMbtu in the next few decades. When prompted as to the volatility of natural gas prices over the near future, Kennedy stated that he sees price fluctuations occurring between the $4/MMbtu and $5/MMbtu range but not outside that range. Kennedy justified his narrow price range on the basis that gas "shut in" can very easily be turned back on.

Gasification technology effectively turns coal into gas, which is then burned and put through a pure hydrogen stream to extract the CO_2 from it. As an independent power producer, Capital Power has been looking at the potential for carbon capture and storage for coal gasification plants to mitigate greenhouse gas emission in their power generating operations for some time. Before the major decline in natural gas prices in the past three years, many assumed that coal might remain a significant fuel source over a long term time horizon. From an operational standard and an engineering feasibility standard Kennedy believes that carbon capture and storage for coal gasification is a technology with reasonable operational viability, and that the technology has reliability characteristics that "we can live with." While confident in the technological feasibility of carbon capture and storage for coal gasification, he qualified his position: there is no reasonable hope that carbon capture and storage for coal gasification become economically competitive with natural gasThe existence of $5/MMbtu natural gas prices effectively precludes new investment in coal gasification plants with carbon capture and storage technology. Speaking to the levelized costs of natural gas plants with carbon capture and storage, Kennedy pointed to work performed by the Electric Power Research Institute, an independent, non-profit research and development institute that conducts research relating to the generation and use of electricity in North America (EPRI, 2012). Figure 9 shows that according to the Electric Power Research Institute the levelized cost of electricity for combined cycle natural gas fired generation ranges from $107/MWh at a carbon price of $10/tonne CO2 to $110/MWh at a carbon price of $40/tonne CO2.

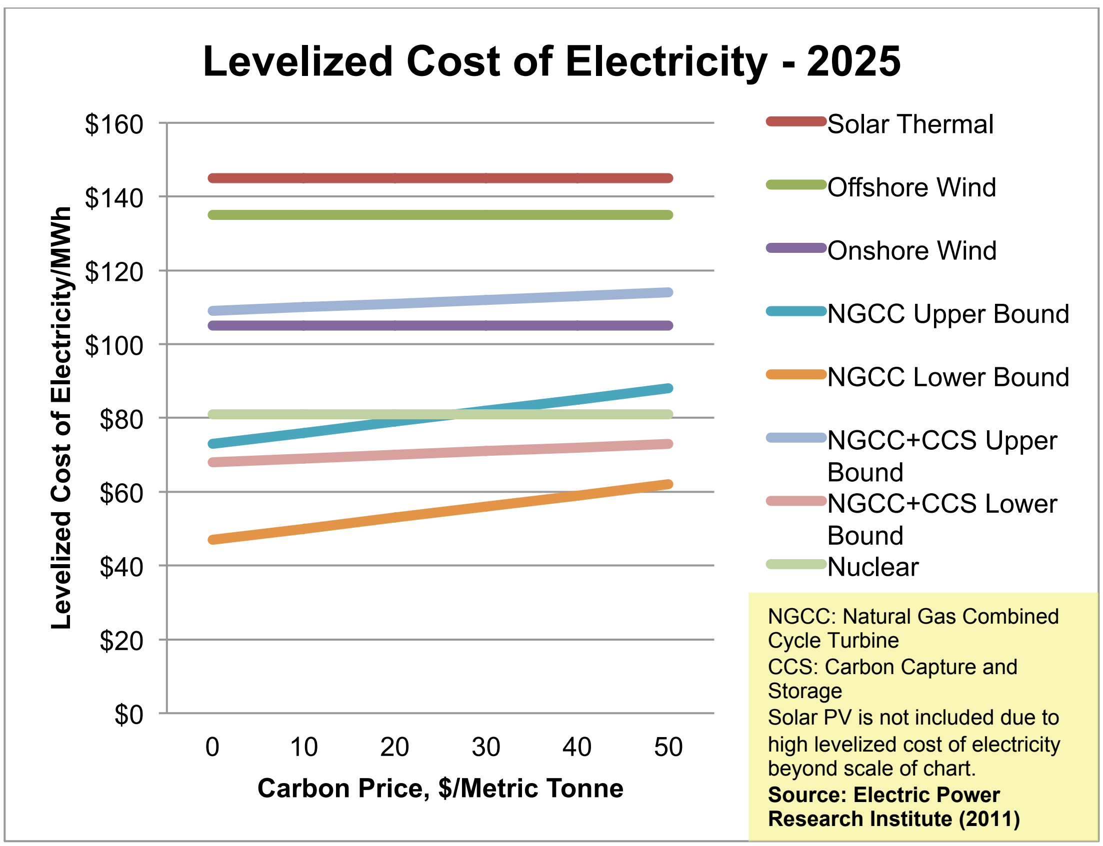


Figure 9. Comparative Levelized Costs of Electricity by Alternative Technologies – 2025

Kennedy noted that there are only a limited number of electricity markets in North America in which generators make generation construction decisions based only on market prices of fuel commodities and capital construction costs; the energy price is not the sole driver of what is constructed. In the United States state level renewable portfolio standards sustain certain renewables by specifying a proportion of new generation has to be met by these renewables. Some cases specify individual technologies based on attractive siting environments and other factors. At bottom, these programs are based on the premise that either a consumer has made a decision to procure energy through a renewable portfolio standard or the direct procurement of energy from a renewable source by a government. Someone, be it a consumer or a government, is willing to pay an above market price for power because the type of generation has certain attributes that they value. Calling this a "pure public policy question", Kennedy concluded that individuals and governments will make decisions that include more than a single fuel type or a single technology. In this environment, Kennedy stated that renewable technologies will find themselves competing with each other and competing with the willingness to pay of governments and the public.

While the willingness to pay by the public and governments for renewable above market energy prices exists, Kennedy thinks that the maximum premium over market price that people and governments will be willing to pay has an upper threshold. Pointing to the example of Ontario, Kennedy noted that renewable portfolio standards and direct procurement efforts have demonstrated is the existence of an upper bound that residential customers will tolerate. Kennedy believes that commercial and industrial customers reach an upper limit of what they will tolerate more quickly than residential customers as they are more responsive to price changes and adjust their operations accordingly. Given the choice of siting an industrial or a commercial facility in a jurisdiction with high versus low energy prices, footloose businesses will migrate.

If you are a consumer-based business, then you might choose to generate added publicity or customer value by using high-cost renewable power. One example is WalMart putting solar panels on top of their store for branding rather than economic reasons. An example he offered was investment in renewable energy as a result of the availability of investment or production tax credits in the United States. What he sees as the real reason a company like Google is purchasing and constructing many wind farms is branding or a large tax shelter created by engaging in such investments. Given his belief that the reduction of greenhouse gas emissions is important for a host of reasons, Kennedy approves offering incentives through the tax system as means to encourage investment in renewables.

Speaking to what level of carbon price would be required to make natural gas fired generation no longer competitive with renewable forms of energy generation, Kennedy stated that it is not as simple as reaching a sufficiently high carbon price. Questions of grid and load reliability are important. Kennedy estimated that a carbon price to make natural gas generation no longer competitive with renewables would be "well north of $200/tonne, more like $250/tonne." In his view the number is so far from being realistically implemented as policy that it is irrelevant.

Kennedy argued that a carbon price is too simplistic a policy instrument to encourage new renewable investment. There are three mechanisms by which emitters can reach these targets, only two of which actually result in emissions reductions. The mechanisms are: emissions reductions at facilities through fuel switching or technological optimization, acquiring offsets, and the payment into a technological research fund to research reducing future emissions. Only the first two result in any real emissions reductions. Reducing emissions output through technological optimization is one option for reducing emissions through a compliance system. Designing the rules for offsets is complicated if it is actually to generate emissions reductions. In Alberta, the regulations state that to qualify as an offset a project must be constructed in Alberta and must be either sequestration of carbon or mitigation. Kennedy stated that while a technological research fund is attractive to some, ultimately its impact on future emissions reductions will be negligible given the jurisdictional and monetary limitations of such a fund in a carbon-rich economy such as Alberta.

Kennedy was emphatic that the displacement of aging coal plants mandated to be shut down will overwhelm all other strategies to reduce GHGs, leaving aside renewable portfolio standards and direct government procurement of renewables. Kennedy provided data on retirement estimates in Alberta based not on market forces, but on the mandated shutdown dates for assets under a combination of recently approved federal regulations for coal-fired generation and Alberta's provincial air emissions regulation. Kennedy explained that while he did not have facility-level emissions data at his disposal and that these facilities will be required to obtain greenhouse gas emission offsets to meet provincial reduction targets, stack emission changes can be approached using the example in Table 3.

Table 3 Emissions reductions of retiring coal based generation with NGCC in Alberta 2018-2019 Source: Martin Kennedy, Capital Power Corporation (2013)

Assumptions:

Plant Capacity Factor: **80%**

Coal Units Emission Intensity: **1 tonne CO2/MWh**

Natural Gas Co-Generation Emission Intensity: **0.37 tonne CO2/MWh**

Example Calculation:

3,777MW of Albertan coal generation offline in 2018-2019 replaced with all NGCC fleet

3,777 MW * 8760 annual hours * 80% capacity factor * 1T CO2/MWh = 26.47 million tonnes

3,777 MW * 8760 annual hours * 80% capacity factor * 0.37T CO2/MWh = 9.79 million tonnes

Net reduction: 26.47 million tonnes – 9.79 million tonnes = 16.68 million tonnes CO2

Table 3 shows that with the replacement of aging coal fired facilities with natural gas fired methods of electricity generation results in annual emissions reductions of 16 MT of CO2, the equivalent of 2% of the total annual Canadian GHG emissions. For context, total utility sector GHG emissions in Alberta in 2009 were 45.9 MT. Kennedy states that the key observation to take away from this is that these emissions reductions are essentially locked in. In his words, “they are what will be achieved literally by doing nothing and letting the market build the lowest cost replacement base load generation (emphasis original).” While Kennedy states that it is possible to supplement these gains in emission reductions through other policies, as the Albertan regulatory framework does, the scale of the change makes it difficult to argue for public monies to be invested in alternatives. Kennedy went on to say that multiplying this phenomenon over a much larger generation fleet such as the coal fleet of the United States – which is also aging and requires replacement even absent restrictive emissions and greenhouse gas laws –

is the reason why he views cheap and abundant gas as the most significant disruptor when it comes to base load power generation.

3.8. Solar PV and Thermal and General Renewables: Zoltan Tompa – Director of Partnerships / Sustainable Development Technology Canada

In Ontario, the levelized cost of electricity of solar PV is not economically competitive with natural gas. With the exception of ideal sites such as those in the American Southwest, feed in tariffs and renewable portfolio standards are the only mechanism by which solar PV can achive cost parity with natural gas. Even with the feed in tariffs that have been introduced in Ontario, the levelized cost of electricity from solar is approximately $400/MWh, excluding the cost of storage mechanisms. Prior to the collapse of natural gas prices in the past 5 years, it appeared that there were attractive market drivers for installation of solar thermal for power generation and heat generation. With natural gas prices at their current historic lows and the forecasts for it remaining low for the foreseeable future, the prospects for solar thermal becoming economically competitive with natural gas are not favourable.

Ontario is the "bright spot" nationally in terms of policy support for solar (by way of feed in tariffs). Characterizing policy support for solar technologies outside of the provincial initiatives undertaken in Ontario as "pretty much zero", Tompa stated that the only real support that can be seen in Canada is early stage technology development delivered through universities by programs such as the Natural Sciences and Engineering Research Council and funding programs such as the Industrial Research Assistance Program. Sustainable Development Technology Canada has moderate levels of investments in technologies that have potential to reduce balance of system costs in solar generation such as improved rack mounted systems for solar PV installations, or micro-converter technologies that reduce balance of system costs.

Pumped hydro storage is the only commercially viable storage technology for utility scale solar PV power generation. The major difference between solar PV and thermal are the siting requirements between the two. While solar PV can reach grid parity in terms of power generation if suitable pumped hydro storage mechanisms are available, solar thermal has siting requirements that depend on the scale of the project. For solar thermal to become economically viable in areas where the solar radiation profile is appropriate for its deployment, the scale must be in excess of 100MW. Solar thermal using molten salt has an inherent storage mechanism that can produce base load power in that heat can be drawn from it at times of peak demand and stored for future use. However, the deployment of solar thermal is unlikely in a North American context because of the paucity of appropriate sites for the deployment of the technology. There is potential for the deployment of solar thermal to provide base load electricity in the American Southwest, but these sites are limited due to competition for land use. Small scale solar thermal deployment on the roofs of buildings has a much more realistic potential for widespread deployment, but is as of yet not economically competitive with fossil fuel fired methods of generation.

In remote communities in regions such as Africa, Brazil, China, India, and Mongolia there is potential for the economic competitiveness of solar thermal integrated with wind and small scale pumped hydro storage with fossil fuel fired methods of electricity generation. In some remote jurisdictions diesel oil used for electricity generation can cost as much as $1000 per barrel, implying levelized electricity cost per MWh in the range of $500. In these contexts a combination of solar thermal (and to a lesser extent PV), wind, and pumped hydro storage are "radically economically viable."

Several storage technologies exist at the pilot stage. Their potential for commercialization can be characterized as 'near term'. One example is an advanced flywheel storage technology project that is supported by SDTC. It involves five flywheel storage mechanisms with a 5MW storage capacity. Calling the technology "proven", the project has been accepted for paid deployment in the Ontario region for the purposes of grid regulation in anticipation of future solar PV installations. Another technology suite developed by Ecamien that has received support from SDTC incorporates advanced lithium ion batteries. It is another potential near term storage solution for solar PV. This technology suite incorporates multiple intellectual properties which revolve around battery management and thermal management systems as well as a supervisory control system that links to the grid.

A storage technology with a high potential for deployment in the context of island nations is Hydrostore. The technology employs bladders of compressed air situated underwater. A project located in the Toronto harbour has already been deployed at a pilot scale. Electricity generated during off peak periods at a low marginal cost is used to compress air. The deeper the compressed air bladders underwater, the more efficient the storage. Hydrostore technology can be integrated with wind and solar electricity generation technologies to transform such renewable projects into base load electricity. The levelized cost of electricity generated from Hydrostore technology is $400/MWh. While this is obviously far above optimum levelized gas-fired generation costs in North America, remote jurisdictions dependent on imported oil or gas may find renewables plus Hydrostore technology economically attractive. The deployment of Hydrostore technology is not suitable without access to deep water.

Another obstacle in the deployment of solar PV and thermal power generation technologies is public opposition to government subsidies and feed in tariffs. There is much lower public opposition to the deployment of solar in Canada than wind, mainly because solar (PV and thermal) does not have the same visual and mechanical footprint as wind. The perceived negative health impacts of wind power have generated high levels of community backlash., There is no analogous opposition to solar technologies.

Tompa did not have data to estimate the carbon price necessary to make solar (PV and/or thermal) economically competitive with fossil fuel fired methods of generation. He was willing to guess that it is at least $75/tonne, but potentially significantly higher. In North American, he was emphatic that without feed in tariffs or renewable portfolio standards solar technologies have no hope in the foreseeable future of becoming economically competitive with natural gas.

While there have been phenomenal gains over the past thirty years in reducing the levelized cost of both solar PV and thermal, efficiency gains occurring at present are minor, with no major breakthroughs in PV or thermal technology expected in the near future. What has greater potential for future reductions in the levelized cost of electricity for solar technologies is increasing economies of scale. Tompa pointed to the example of China in which the state has effectively taken on capital expenditure costs for solar PV manufacturing facilities, leaving only operating expenses for the state owned firms to assume. This reflects an expectation on the part of the Chinese government of both scale economies emerging and a political decision on their part to subsidize the production of solar PV panels (Hook & Chaffin, 2012). This has effectively priced out global competition for the manufacturing of solar panels (Hook & Chaffin, 2012). However, potential for solar PV to become cost competitive with natural gas fired generation in the near future has essentially evaporated.

4. Summary of Elite Interviews

Table 4 summarizes the findings of the elite interviews. The most significant finding is that CANDU-6 and ACR-700 (and by extension ACR-1000) reactors probably have a much lower levelized cost of electricity than that reported by the EIA and the IEA ($57-63/MWh on a public basis, $83.66/MWh on a pure “merchant” basis compared to $111/MWh). In fact, provided actual capital and operating costs are close to projections, the levelized cost of electricity from nuclear power generated by CANDU technology is cost competitive with the levelized cost of electricity from natural gas, even at present low natural gas prices. The explanation for this significant discrepancy may be that the EIA and the IEA focused their analysis of ‘Advanced Nuclear’ on the Westinghouse AP1000 and SMR designs. As the first two prototype AP1000’s are currently being constructed, no learning by doing or cumulative technological efficiency gains through economies of scale have been realized. Future research should be conducted to reconcile this discrepancy in the literature.

The elite interviews have confirmed the findings of the EIA and the IEA when it comes to wind, solar (PV and thermal), and geothermal being unable to function as readily dispatchable base load electricity generation technologies on a global scale. Without a carbon price of $200-$300, wind and solar (PV and thermal) cannot compete with natural gas fired methods of electricity generation. The absence of commercially viable electricity storage technologies outside of pumped hydro storage likewise precludes a significant penetration of electricity markets by solar. The situation is slightly more favourable for wind being able to make up 20% of a typical national jurisdictions energy mixture, but NIMBY and NAMBY concerns over disruptive visual impacts of the technology remain a significant barrier, as does its requirements for new transmission infrastructure. Geothermal suffers from its deployment being contingent on the availability of ideal sites located near demand centres. Wind and solar (PV and thermal) fare better in the context of remote communities and island nations where geography favours these technologies.

While fusion may enter the energy mix later in this century, it is impossible at this time to predict when or if thermonuclear fusion technologies will be commercialized. Materials science and fundamental physics are significant obstacles. Even if a prototype reactor is constructed, it will still take decades for fusion, be it magnetic confinement, target, or inertial to achieve significant penetration into a nation's energy supply. Of the potential concepts put forth, magnetized target fusion is the most attractive from an economic perspective, costing several orders of magnitude less for prototype construction than its magnetic confinement counterparts.

Table 4. Summary of Elite Interviews

Technology	Current Levelized Cost of Electricity	Projected Decline in LCOE over 30 years	Estimated required Carbon Price/tonne to become competitive with Natural Gas	Market and Technical Constraints	Capable of providing baseload without storage	Commercialized	Importance of Societal Concerns (NIMBY/NAMBY)
Run of River Small Hydro	$100-$120/MWh	Minimal	$120	Lack of cost competitive siting opportunities	Yes	Yes	High, due to environmental concerns and visual impact of transmission
Wind	$75/MWh	20-30% from $75/MWh	$200-$300	Storage Optimal generation sites located far from demand centers Utility/public unwillingness to meet demand through new generation construction High transmission costs	No	Yes	High, due to visual impacts of transmission and generation infrastructure
Solar PV	$400/MWh	Minimal	> $75 (possibly	Storage Lack of viable	No	Yes	Medium, due to visual impacts of

Technology	Current Levelized Cost of Electricity	Projected Decline in LCOE over 30 years	Estimated required Carbon Price/tonne to become competitive with Natural Gas	Market and Technical Constraints	Capable of providing baseload without storage	Commercialized	Importance of Societal Concerns (NIMBY/NAMBY)
			$200-$250)	sites for deployment Unattractive for utility scale generation			transmission
Solar Thermal	$230-$260/MWh	Minimal	> $75 (possibly $200-$250)	Very limited siting suitability	Yes	Yes	Medium, due to visual impacts of transmission
Geothermal	$70-$100/MWh	Uncertain	British Columbia: $0 Elsewhere: Variable, but minimal	Very high upfront capital costs Significant lack of public knowledge Regulatory void Very high exploration costs Investor uncertainty Transmission costs from remote sites	Yes	Yes	Medium, due to visual impacts of transmission
Generation III/III+ Nuclear	$57-$63/MWh (public basis)	Minimal to insignificant	$0	Slow growth of power demand	Yes	Yes	Very High due to public perceptions

Technology	Current Levelized Cost of Electricity	Projected Decline in LCOE over 30 years	Estimated required Carbon Price/tonne to become competitive with Natural Gas	Market and Technical Constraints	Capable of providing baseload without storage	Commercialized	Importance of Societal Concerns (NIMBY/NAMBY)
(CANDU 6 and ACR1000)	$83.56 (merchant basis) (CANDU 6 and ACR 1000) $111/MWh (Westinghouse AP1000/SMRs)			due to sluggish economic growth Concerns regarding catastrophic radiation release			of nuclear power
Generation IV+ Nuclear	N/A	Expected to become commercialized in 2030	N/A	Lack of increased demand for fissile material	Yes	No	Very High, due to public perceptions of nuclear power
Terra Power Generation IV TWP-R	N/A	Expected to be cost competitive with natural gas	Estimated to be $0	Prototype to be constructed 2022	Yes	No	Medium, due to radically different risk profile than Gen III and III+ designs
Magnetic Confinement Fusion	N/A	N/A	$200	First DEMO reactor to be constructed 2050 Materials science obstacles	Yes	No	Low

Technology	Current Levelized Cost of Electricity	Projected Decline in LCOE over 30 years	Estimated required Carbon Price/tonne to become competitive with Natural Gas	Market and Technical Constraints	Capable of providing baseload without storage	Commercialized	Importance of Societal Concerns (NIMBY/NAMBY)
Magnetized Target Fusion	N/A	Decline to $40/MWh one decade after prototype construction	At present natural gas prices: $15-$30/tonne	Success of technical test of fundamental physics First of kind prototype construction Significant engineering challenges	Yes	No	Low

5. Conclusion

There is no magic bullet to bring about an electricity generation regime that does not emit greenhouse gasses. A mix of established and emerging energy technologies will be required should a particular jurisdiction wish to pursue this goal. In terms of providing base load electricity to human population centres, governments are faced with clear options. Unfortunately, the implementation of these options faces significant NIMBY and NAMBY opposition.

Wind power can probably make up 20% of a typical national jurisdiction's electricity supply at a levelized cost below $100/MWh. Above this 20% threshold, the costs associated with transmission and distribution drive the levelized cost of additional wind capacity to economically untenable levels. NIMBY and NAMBY concerns regarding the visual impact of wind farms, perceived health impacts due to the acoustic vibration of wind turbines, and the associated transmission infrastructure will have to be countered if wind is to be a significant share of capacity. Such concerns are the key obstacle to wind power increasing its electricity mixture penetration. Significant public education campaigns may contribute to social bandwagon effects on behalf of wind. Further research should be conducted to assess successful public education programs in jurisdictions which have achieved a 20% wind share of generating capacity.

There is very limited potential for additional large hydroelectric capacity to be developed given the significant and often intractable obstacles to its implementation. Be they political, environmental, NIMBY/NAMBY, or security based, these obstacles are coupled with the reality that almost all of the low hanging fruit of global large hydroelectric potential has already been exploited. In terms of run of river small hydro, the levelized cost of the technology is economically prohibitive, even at high carbon prices. NIMBY and NAMBY concerns regarding run of river small hydro are even more acute than those experienced by wind power. Public opposition to new hydroelectric construction and its associated transmission infrastructure is such that even the most robust of public education programs can be expected to have little effect. Also, in the majority of cases the costs of transmission infrastructure significantly increase the delivered cost per MWh.

Geothermal energy cannot be expected to play a significant role in a national jurisdiction's energy mix for two major reasons. The first is that geothermal energy resources are located far away from major electricity demand centres, which raises the same high transmission costs associated with run of river and wind. The second is that even if every geothermal resource on the planet was developed to its maximum potential, only 2TW of electricity could be generated (Murphy, 2012). Geothermal energy remains an attractive niche technology for remote communities and areas with favourable geological heat profiles. In Canada, with the exception of British Columbia, there is a complete policy and regulatory vacuum for geothermal energy in terms of its exploration, development, and sale. This regulatory void is a significant obstacle to new geothermal development. Future research should be conducted as to the establishment of a policy and regulatory framework. This policy framework should include a uniform and scientifically recognized code of evaluating geothermal resource potential. The establishment of such a policy framework may address significant existing concerns as to the uncertainty of geothermal energy investments for investors and utilities and lead to higher levels of investment.

Solar PV and thermal are the two most expensive renewable technologies for generating electricity in terms of levelized cost, and as such require massive levels of public subsidy for new capacity to be constructed. The problem of generation intermittency inherent to solar PV, and to a lesser extent solar thermal, is such that solar cannot function as a reliable source of base load electricity. There are no commercialized or economically viable storage mechanisms outside of pumped hydro. There are two exceptions to this constraint. The first is that small island nations could see solar PV or thermal in tandem with emerging bladder storage technology. The second are areas near large deserts that receive high levels of solar radiation (such as the American Southwest). However, most human population centres are located very far from such sites.

Of the non-carbon technologies, only Generation III and III+ nuclear reactors (such as the CANDU 6, EC6, ACR-700 and ACR-1000 designs) are potentially competitive with natural gas generation technologies in provision of base load electricity. Of these new designs, the CANDU 6, EC6, CANDU ACR-700 and ACR-1000 are the most promising. CANDU 6 reactors are in operation around the world. CANDU is actively working with the Chinese government to generate electricity from thorium fuelled CANDU reactors in the near future. Advanced CANDU reactors built in China have been constructed without experiencing the significant cost overruns and delays that have plagued competing Generation II, III and III+ designs. The CANDU reactors have highly attractive safety profiles, possessing passive safety mechanisms that render them 'walk away safe' in the event of a catastrophic event or human error on the part of the operators. NIMBY and NAMBY concerns regarding nuclear may be more significant than analogous concerns associated with small hydro and wind power. However, should decision makers prioritize the establishment of a national electricity generation regime that significantly decreases or eliminates greenhouse gas emissions, they must acknowledge the reality that renewable technologies cannot and probably will not meet base load criteria at acceptable levelized costs.

In conclusion, Canadian decision makers should give high priority to the construction of Generation III and III+ CANDU reactors across the country.

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Appendices

Appendix A. Interview Script

The interviews will be semi-structured to facilitate two way communication between the interviewer and interviewee. These interviews will focus on data for the following variables of case studies:

Institutional factors – Current initiatives to bring advanced energy generating technologies to commercialization, including industry and governmental support in the areas of scientific research and funding.

Technological factors – Potential for emergence of advanced technologies

Social factors – Potential for public opposition to advanced technologies

Economic factors – Potential for advanced technologies to compete with fossil fuel fired methods of generation

Disruption factors – Potential for each technology to replace existing electricity and heat generation regimes.

Industry factors – The current state of advanced electricity and heat generating technologies that are nearing or have achieved commercialization and the potential for their deployment.

Representation of the public interest

Experiences

Opportunities and Threats

Interview Questions

What are the most significant emerging advanced energy and heat technologies that have a high potential for existing regime disruption?

What are the most significant challenges involved in commercializing these advanced energy technologies?

What are the levels of support in the industrial and governmental sectors for the advancement of these technologies?

What is the current levelized cost of electricity of technology X?

What impact has learning by doing and technological advancement had on technology X?

What is the probability that technology X will achieve a levelized cost of electricity that is competitive with existing methods of fossil fuel fired electricity and heat generation?

What are the greatest technological challenges for technology X?

What are the most significant endogenous challenges that technology X faces in being accepted as an alternative to fossil fuel generation y the general public?

What are the most significant challenges in terms of infrastructure for technology X in terms of balance of plant and grid integration?

What are the most significant risks to the public of technology X in terms of safety?

What is the potential for existing electricity and heat generation regime disruption?

What level of carbon price would be required for your preferred technology to be competitive with fossil fuel fired methods of generation?

What is the number of lives lost per MWh for technology X?