THE ECONOMICS OF VERY SMALL MODULAR REACTORS IN THE NORTH

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ABSTRACT – Many communities in Canada's far north rely on diesel generators for their electricity. With an average production cost close to $50/kWh and many generators nearing their end of life, an opportunity exists for alternative technologies to enter the market. Nuclear power plants (NPPs) have provided Ontario with reliable, low cost, low CO_2 electricity for several decades. However, the electrical capacity of existing NPPs far exceeds the demand requirements in the far north. This paper presents a life cycle cost analysis of a very small modular light water reactor (vSMR), demonstrating that a vSMR could reduce electricity costs in the north. The magnitude of the savings depends on the degree of modularization and the price of carbon.

1. Introduction

Many communities in Canada's northern territories (the North) rely exclusively on diesel generators for their electricity [1]. These communities are interested in alternative electricity sources that would mitigate against increasingly variable diesel fuel costs and growing concerns over greenhouse gas emissions. With a significant portion of the diesel generation infrastructure nearing end of life, now is an ideal time to reduce the reliance on diesel electricity [2].

The nuclear power plants (NPPs) in operation today are large, with electrical capacities commonly exceeding 1,000 MWe. These NPPs are not suitable for these remote communities since electricity demand in these areas is limited (2-10 MWe) and the cost of transmission lines ($150,000/km to $300,000/km) prohibit inter-community grid connections, which would need to span hundreds of kilometers [3]. However, several very small modular reactor (vSMR) concepts are under development, which have an electrical capacity of <15 MWe and are specifically designed for remote communities [4]. In addition to the smaller electrical capacity, these designs include improved safety and reliability features making them excellent options for the harsh environments in the North, provided they are economically competitive with other options. As these vSMR designs are still under development, this paper examines a generic LWR design, instead of focusing on a specific design. This yields a high level analysis that can later be adapted for a specific SMR design.

This paper estimates the levelized unit electricity cost (LUEC) of a 10 MWe light water reactor (LWR, referred to as 'the vSMR') based on currently available information, giving special consideration to the unique challenges of construction and operation in the North. The LUEC of the vSMR is compared with the cost of a diesel generation facility to demonstrate that the vSMR could be competitive in the North. All costs are reported in 2015 US dollars, escalated based on the U.S. Bureau of Labor and Statistics consumer price index (CPI) [5], unless otherwise indicated.

2. Diesel Costs

Electricity generation costs can be separated into three main categories: capital costs, operating costs and decommissioning costs. These costs are levelized over the total electricity produced to determine the LUEC ($/kWh), which can then be compared with other sources to assess whether an economic advantage exists. The decommissioning cost of a diesel generator is minimal, therefore this estimate focuses only on the capital and operating costs.

2.1 Capital Costs

In 2011, an application was made by the Qulliq Energy Corporation (QEC) for a new 2 MWe diesel facility, which includes four 520 kWe generation sets, in Taloyoak, Nunavut [6]. The overnight cost estimate was approximately $9 M, therefore, a 10 MWe facility is expected to cost $22 M based on expected economics of scale. The diesel plant is expected to be constructed in two years and operated for at least 40 years [6]. The interest during construction (IDC) is calculated to be $1 M using the continous s-curve spending pattern formula from the Generation IV International Forum (GIF) economic model [7]. Making the total estimated capital cost of the 10 MWe diesel facility $23 M or $0.0124/kWh[1].

2.2 Operating Costs

This analysis assumes the 10 MWe diesel generator set will produce 78,840,000 kWh annually, which is comparable to the vSMRs annual electrical output. The QEC reports an average consumption rate of 3.71 kWh/L for their diesel generators [2]. Therefore, at a unit cost of $0.75/L [8], annual diesel fuel costs are estimated at $16 M/year for a 10 MWe diesel facility. In 2015, fuel and lubricants made up 44.6% of total operating and maintenance (O&M) costs [2], therefore the total O&M cost of the 10 MWe diesel facility is $36 M or $0.455/kWh ($0.2029/kWh for fuel and $0.2521/kWh for non-fuel O&M). As a result of these high O&M costs, diesel generators are a very expensive method of electricity generation.

Furthermore, for every litre of diesel fuel that is burned, roughly 2.6 kg of carbon dioxide (CO_2) is produced [9]. Annually, the 10 MWe diesel facility will produce 54,600 tonnes of CO_2 per year. If the carbon tax in British Columbia ($30/tonne of CO_2, [10]) were to be implemented nationwide, this would result in an additional $2 M/year in operating costs or $0.0210/kWh.

3. Very Small Light Water Reactor

The LWR technology has been deployed in several countries around the world with several decades of successful operating experience. The low cost of electricity and proven design makes the LWR an excellent contender for deployment in the North provided the electrical capacity can be scaled to match demand without sacrificing quality or increasing the cost of electricity (compared to diesel).

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[1] This assumes an annual interest rate of 3% and an availability factor of 90%.

3.1 Capital Costs

Capital costs include three major components: overnight cost, cost of initial fuel load and IDC. The Energy Policy Institute at Chicago (EPIC) estimated the overnight capital cost of 1,000 MWe LWR to be $4,210/kWe in 2011 US$ [11]. This was escalated to $4,436/kWe in 2015 US$ using the annual CPI [5]. The overnight cost of a 10 MWe vSMR before any costs/savings specific to the modular design is estimated as follows[2]:

$$Overnight\ Cost(SMR, \$M) = Cost(Large\ NPP, \$M) * \left(\frac{SMR\ MWe}{NPP\ MWe}\right)^{n} = \$4{,}436M * \left(\frac{10}{1000}\right)^{0.55}$$
$$= \$352\ M$$

The overnight cost was broken down into three subcategories: direct costs (70%), indirect costs (10-15%) and owners' costs (15-20%) [11] and adjusted to account for the unique advantages and disadvantages of SMRs. These challenges include:

- the additional material is required for supports needed to secure modules during assembly [12];
- unique aspects of SMR on-site construction, including burial of reactor vessel, larger cranes/hoists needed to move modules during construction, more robust instrumentation;
- design simplifications such as the integrated pressure vessel; and
- factory fabricaiton of modules, which will introduce economies of replication, decrease labour costs and allow for bulk materials purchases.

Considering all these factors, the final overnight cost for the vSMR was estimated at $289 M.

Current LWRs are fuelled with approximately 66,000 kg of uranium enriched to 4% ^{235}U. One factor affecting neutron economy in a reactor is the physical core size. Since the vSMRs core is significantly smaller, a higher enrichment is required. This report assumes a 1,000 kg core made of uranium enriched to 15% ^{235}U. Using the unit fuel cycle costs in [13], the initial fuel core was estimated and recorded in (Table 1).

Process Step	Unit Cost	Units	Initial Core Cost ($M)
Uranium Ore	83	$/kgU	3
Conversion	11	$/kgU	<1
Enrichment	122	$/SWU	3
Fabrication	331	$/kgU	<1
		Total	**7**

Table 1 vSMR Initial Core Costs

The final component of the total capital cost is the IDC. The IDC is calculated based on the overnight cost plus the cost of the initial core using the continuous interest formula from the GIF economic model [7]. The IDC cost was calculated at $23 M over 3 years of construction for the vSMR.

[2] The IAEA recommends a scaling factor (n) between 0.4 and 0.7; the midpoint value of 0.55 was used in this analysis [11].

Therefore, the total capital cost of the vSMR is $319 M. The annual capital recovery cost (including interest) was used to estimate the levelized unit capital cost at $0.236/kWh based on a 90% capacity factor and a 40 year expected operating life.

3.2 Annual Operating Costs

Annual operating costs are sub-divided into fuel costs and non-fuel costs. The vSMR is assumes to have a refuelling cycle of five years; where one-fifth of the core is replaced annually. Using the unit costs that are included in Table 1 above, the annual fuel cost for the vSMR is estimated to be $1 M/year (or $0.018/kWh).

The non-fuel O&M costs were estimated based on a 2015 report from the Nuclear Energy Institute (NEI) that estimates non-fuel operating costs for a stand alone reactor to be $27.15/MWh [14]. Not all minimum staffing requirements directly scale with size, therefore the NEI unit cost estimate was increased by 50% for the vSMR to account for the lack of economies of scale in operations. The annual operating cost for the vSMR was estimated at $3 M/year or $0.041/kWh.

3.3 Backend Costs

Backend costs include the used nuclear fuel (UNF) disposal costs and the reactor decontamination and decommissioning (D&D) costs. Canada's current plan is to dispose of all UNF in a deep geologic repository (DGR), therefore it was assumed that the UNF produced from a vSMR would also be stored in a DGR. Using the unit fuel cycle costs in [13], the UNF disposal cost was estimated and recorded in (Table 2).

Process Step	Unit Cost ($/kgHM)	vSMR UNF Cost ($M)
Wet Storage	331	3
Dry Storage	133	1
Waste Condtioning	110	1
Transportation	125	3
DGR	718	6
	Total ($M)	**13**
	Total ($/kWh)	**0.002**

Table 2 UNF Dispositioning Costs

The D&D costs for each reactor are still widely unknown as few commercial reactors have completed D&D. Many estimate D&D costs for larger NPPs to be between 25% and 35% of the overnight capital cost. However, the D&D costs for the vSMR are not expected to scale linearly with electrical capacity due to the economies of scale that are generated in a larger D&D project. In this report, D&D costs for the vSMR are estimate at 40% of the overnight cost; $116 M or $0.012/kWh[3].

4. Final Results

[3] This value was amortized over the 40 year operating life [7].

The LUEC estimate for the vSMR was lower than the estimated LUEC for a diesel facility. Therefore, a vSMR could be a cost competative alternative to diesel in the North. To confirm the vSMRs cost advantage, specific consideration must also be given to the unique challenges of construction and operation in the North; such as a lack of skilled workers, extremely limited infrastructure, permafrost and other harsh environmental conditions. A northern adjustment factor based on the cost of diesel electricity generation in Nunavut relative to the cost of diesel electricity generation in the continental United States [15] was established to account for these challenges. This factor was applied to any task that was assumed to take place in the North. The result (Table 3) shows that the vSMR could provide a possible savings between $0.013/kWh and $0.034/kWh over diesel, depending on whether or not a carbon tax is impelemented. For a 10 MWe reactor with a 90% capacity factor, this amounts to a savings of $1-$3 M per year, for a total of $41-$107 M over the 40-year life of the reactor.

	Diesel	Adjusted vSMR
Capital Cost	0.012	0.345
Fuel Cost	0.202	0.018
Operating Cost	0.251	0.067
Carbon Price	0.021	-
UNF Dispositioning	-	0.005
D&D	-	0.018
Total without Carbon Tax	**0.466**	**0.453**
Total with Carbon Tax	**0.487**	**0.453**

Table 3 Adjusted LUEC Results ($/kWh)

5. Limitations in this Analysis

An SMR industry does not currently exist in Canada and potential reactor sites have not yet been identified or validated. Therefore, this analysis did not focus on a specific community in the North. Instead, it was assumed that a community existed in the North that required 10 MWe of baseload electrical capacity. The SMR and the diesel facility required to meet this demand were evaluated, however any additional facilities required for load following, district heating or backup power were not considered.

Costs for the area were assessed at a high level. Additional costs that should be considered once a potential reactor site is identified are:

- The development local infrastructure required to support the construction and operation of the SMR such as transportation and telecommunicaiton.
- Location specific transportation and electricity costs.
- The load following needed to match the demand profile of the community.

Finally, the northern adjustment factor was intended to provide a general estimate of the increase in costs due to the challenging conditions in the North. However, the cost profile of a diesel plant is very different than the cost profile of an vSMR, therefore it is likely each are impacted differently.

6. Comparison to Other Analysis

Althought the estimate in this paper does have some limitations, it was found to align well with other similar estimates. A recent study on the feasibility of SMR deployment in Ontario was performed for the Ontario Ministry of Energy [16] which evaluated nine different SMR technologies. The following compares the results of this paper with those found that feasibilty report, and also to a cost estimate published by an SMR vendor [17].

6.1 Diesel Estimates

In [16], a medium-speed diesel engine is estimated to have an inital captial cost of $2,000/kWe and a non-fuel operating cost of $15/MWh. Therefore, a 10 MWe facility is estimated to have a capital cost of $20 M and a non-fuel operating cost of $1.2 M. The capital cost is very close to the $23 M estimate in this paper, however the non-fuel operating cost is much lower. The non-fuel operationg cost estimate used in [16] was based on in-house knowledge and was specific for an Ontario application, where the estimate in this paper is based on the QEC's annual diesel generation O&M expenses breakdown. Therefore, it is assumed that the difference in non-fuel O&M costs is a result of the increased challenges of operating in the North.

The analysis in [16] also included a forecast of long term diesel prices, which calculated a cost of $0.99/L[4] in 2015 rising to as high as $2.39/L[4] in 2040. This paper used a diesel fuel cost of $0.75/L based on historic prices [8]. Therefore, the fuel costs estimate in [16] ($0.305/kWh) is higher than the $0.202/kWh estimated in this paper.

Overall, the total LUEC estimated reported in this study ($0.466/kWh - $0.487/kWh) was found to be between 33%-55% higher than the estimate in [16] ($0.30/kWh - $0.35/kWh). This difference was expected due to the unique challenges of construction and operation in the North and is in line with the northern adjustment factor used in this paper.

6.2 vSMR Estimates

The SMR estimates in [16] included two integreal pressurized reactors, however cost estimates for each SMR were not provided. That report provided a LUEC range of $0.193/kWh to $0.288/kWh for all nine reactors [16]. This paper estimates the total LUEC of the vSMR to be $0.309/MWh before the northern adjustment factor. Although [16] did not detail the methodology used to derived their estimates, the difference is likely related economies of scale since the demand for power is greater in northern Ontario than it is in remote communities located in the North.

NuScale, an integral light water SMR vendor, has also published a cost estimate for their SMR. In 2014 US dollars, their SMR is estimated to cost $5,078/kW to construct, with total LUEC costs between $0.090/kWh and $0.101/kWh [17]. These estimates are based on a multi-reactor facility, with up to 12 reactor units operated from a single control room. This type of facility will result in economies of scale that the single vSMR in this paper cannot achieve, explaining the discrepancy between the cost estimates in this paper and those provided by NuScale.

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[4] Canadian 2015 dollars.

7. References

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