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Exploring the Transitional Role of B.C. Natural Gas Supply in Transportation and HVAC Systems

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***Abstract*—** The aim of this paper is to present appropriate metrics and tools to investigate the transitional role of natural gas (NG) resources in the context of climate change mitigation policies. In this regard, we identified potential pathways for conversion of B.C. NG resources into diverse fuel supplies. Specifically, road transportation and heating, ventilation and air conditioning (HVAC) system of buildings are two major greenhouse gas (GHG) emitting sectors in the BC economy. We propose three metrics in order to discover the optimal promising use of NG in these sectors of economy. A hybrid economic model, which has technical details and real market data equilibrium feedbacks, is introduced to study different climate mitigation policies. Second, exergy efficiency is used as a thermodynamic metric to help to direct the economy model. Third, alternative ways to account for the temporally varying forcing of GHGs are introduced. Finally, some preliminary results are presented comparing the exergy efficiency of NG use in various HVAC and transportation pathways.

Keywords- Natural Gas (NG); Exergy Efficiency; Pathway Analysis; Climate Metrics; Hybrid economic model

I. INTRODUCTION

One important aspect of NG deployment in BC is its relatively inexpensive cost and potentially lower GHG emissions compared to other fossil fuel options. Thus, NG has attracted the attention of academia and policy makers to this source of energy. The aim of this research is to propose an alternative to the advocated option of LNG export to foreign markets, in which BC's conventional and unconventional NG can best be used domestically in the near term and importantly how it could pave the way towards low and zero carbon energy systems in the future. Currently, GHG emissions in the road transportation, residential, and commercial sectors in BC contribute to 24%, 6.8%, and 4% respectively of total emission according to the 2013 inventory list [1]. We will focus on economic, policy, and technical aspects of the development of NG systems as transitional to a renewable energy system. This means conventional/ unconventional NG resource development would be in place for 30–50 years. Then, with further strict carbon policy measures and technical maturity of alternative fuel systems, many sustainable options like hydrogen production and distribution network systems, bio-methane, solar, wind, or geothermal systems will emerge for utilization in transportation and HVAC systems. The key concern here is to find optimal pathways for employing BC NG resources while incurring minimum environmental impact and steering the BC economy toward sustainable development. This paper is organized as follows. Section II demonstrates the transition concept for the road transportation and HVAC systems. Section III introduces exergy, alternative climate metrics, and hybrid economic models. Section IV presents some preliminary results on exergy metrics. Finally, section V provides overall conclusions and proposes directions for the future research.

II. PROPOSED ALTERNATIVE PATHWAYS

Utilization of NG in transportation is possible through a number of pathways including: 1) H_2 (Reforming Plant) →Fuel Cell Vehicle; 2) Electricity (Power Plant) → Battery Electric Vehicle; 3) Diesel & Gasoline (Gas to liquid plant) → Diesel & Gasoline Vehicle; 4) LNG (Production Plant) → LNG vehicle; 5) CNG (Local Compression & Refueling) → CNG vehicle. Fig. 1 illustrates these concepts and how in the future the transition from NG resources to renewable energy is possible as a result of technical maturity and gradually increasing carbon mitigation policy measures.

NG could drive HVAC systems either as a form of heat or electricity. The Building Technologies Office of the U.S. Department of Energy in a comprehensive report [2] examined alternative HVAC systems without hydroflurocarbon (HFC) refrigerants. The report introduced promising technologies for deployment in HVAC systems. The Evaporative Liquid Desiccant Air Conditioner and the Vuilleumier heat pump acquired top positions among thermally driven systems. Also, Magnetocaloric, Membrane Heat Pump, and Thermoelastic systems obtained the highest ranks for electricity driven systems. Among these promising technologies, the Vuilleumier heat pump, Magnetocaloric, and Membrane Heat Pump are emerging technologies while Evaporative Liquid Desiccant Air Conditioner and Thermoelastic systems technologies are still in the R&D phase. *Fig.2* illustrates these concepts and shows how in the future the transition from NG resources to renewable

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energy is possible for building HVAC systems as a result of technical maturity, further R&D, and gradually increasing carbon mitigation policy measures.

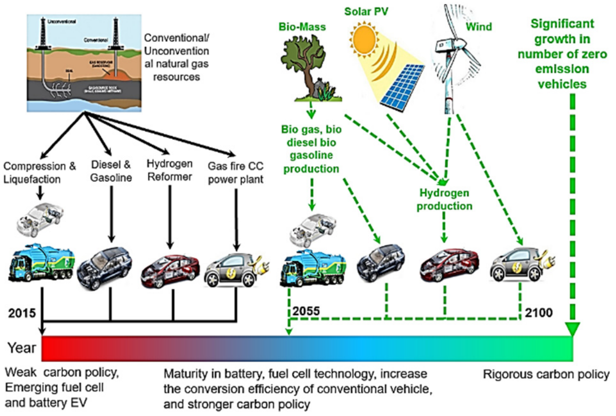

Figure 1. Transition of transportation from NG resources to alternative sustaiable feedstock

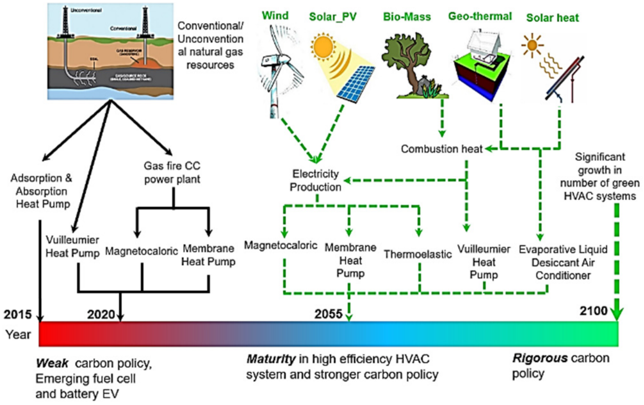

Figure 2. Transition of HVAC systems from NG sources to alternative sustaiable feedstocks

III. EVALUATION METRICS

A hybrid economic model will predict consumers' response to alternative technology choices under different climate policies. Exergy efficiency can be used to inform the economy model toward capturing alternative technologies for HVAC and transportation systems based on NG supply. Finally, alternative GHG accounting metrics aim to be incorporated in the hybrid economy model in order to better quantify emission projections.

A. Hybrid Energy Economic Model

Energy-economic models conventionally were classified into top-down and bottom-up approaches. Top down models capture each sector of the economy in an aggregated format, while the bottom-up approaches can capture many technical details at each sector of the economy [3]. CIMS is an energy-economic integrated hybrid simulation model, which combines technology explicit features and partial macroeconomic feedbacks, as well as the realistic behavior of the market [4]. It can predict firms' and households' response to various mitigation policies in terms of technology choices [5]. For better future predictions, it is necessary to represent all technological choices of the energy market.

The market share model contains both financial and behavioral realism elements, such as discount rate (*r*), non-financial cost (*i*) (technological risks or barriers), and market heterogeneity (*v*) which represents consumer perceptions and preferences. The following equation presents the core of the CIMS model [5]:

$$MS_j = \frac{\left[CC_j \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}} \qquad (1)$$

where MS_j indicates the market share for the technology (*j*) in each sub-sector of the economy. CC_j, MC_j, and EC_j refer to capital cost, maintenance cost, and energy cost of the technology, *j*, respectively. The n_j parameter indicates the life span of the technology.

B. Exergy

The concept of exergy takes into account the effect of an energy resource and its environment, quantifying the maximal available work as the system equilibrates with the environment (dead state). Total exergy is the sum of the individual forms of exergy including internal, external, as well as radiation and nuclear exergy. The internal exergy used in this work is the combination of thermal, mechanical, and chemical exergy, defined by Simpson [6] as:

$$X_{int} = X_{TM} + X_C \qquad (2)$$

$$X_{TM} = (H - T_oS)_{RS} - (H - T_oS)_{TM} \qquad (3)$$

$$X_C = G_{TM} - \sum_i \mu_{i,o}\, N_i - \sum_j \left(\sum_i \mu_{i,o}\, N_i \frac{v_{i,o}}{v_j}\right) N_j \qquad (4)$$

where the subscripts RS and TM mean resource state and thermal-mechanical dead state, respectively. G is the Gibbs Function, the second term is the diffusive work potential of environmental species (i) exist in the resource and the last term is the reactive and diffusive work potential of non-environmental species exist in the resource. Also, μ is the chemical potential, v is stoichiometric coefficient, and N is the moles of species. The exergy efficiency metric was applied by Waller et al. [7] in the form of a well-to-wheels analysis in order to compare different conversion pathways for NG resources in the road transportation sector. They defined process chain exergy efficiency as follows:

$$\eta_{ex} = \frac{X_{out}^1}{X_{in}^1}\frac{X_{out}^2}{X_{in}^2 = X_{out}^1}\frac{X_{out}^3}{X_{in}^3 = X_{out}^2} = \frac{X_{out}^3}{X_{in}^1} \qquad (5)$$

The chain exergy efficiency metrics can help inform the economy model by capturing more promising technologies. Adding these most technically efficient choices into electricity, residential, commercial, and transportation sectors will consequently upgrade the economy model to better predict GHG emissions of the B.C. economy.

C. *Dynamic climate metrics to account for GHG emissions*

A challenge in comparing alternative energy system pathways is how to account for the properties of different greenhouse gases (emitted from energy systems) and convert them in to a unique value, often in equivalent tons of (CO_2e). Static climate factors such as the standard global warming potential (GWP) [8] undervalue decadal scale gases like methane, when the mitigation target year is approached. Trancik and Edwards [9] concentrated on this deficiency and devised new dynamic metrics for a global warming potential conversion factor that they called cumulative climate impact (CCI) (equation (6)) and instantaneous climate impact (ICI) (equation (7)) in which t_s is the stabilization year, t is the current year, and RF is the temporally varying radiative forcing of the greenhouse gases. They demonstrated that using a static climate factor of 100 years to determine the equivalent methane to CO2 impact could overestimate the benefit of promising energy technologies likes CNG vehicles over the next several decades.

$$CCI = \frac{\int_t^{t_s} RF(CH_4)\,dt}{\int_t^{t_s} RF(CO_2)\,dt} \tag{6}$$

$$ICI = \frac{RF(CH_4)}{RF(CO_2)}|_{t_s} \tag{7}$$

Requisite GHG emission factors and energy consumption for NG conversion from well extraction to end user will be extracted from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET) [10].

IV. PRELIMINARY RESULTS

In this section, some preliminary results of this work related to the exergy analysis component are presented.

A. *Exergy analysis of simple NG liquefaction cycle:*

In order to compare domestic NG uses to LNG export, the exergy destruction rate for each component of a non-ideal Linde-Hampson cycle (neglecting heat transfer) at the steady-state condition (without chemical reaction) can be expressed as [11]:

$$\dot{X}_d = -\dot{W}_{cv} + \sum_i \dot{X}_i - \sum_e \dot{X}_e \tag{8}$$

where indexes d, i, and e denote for destruction, inter, and exit. The operating condition is assumed to be: inlet temperature =15 ºC, inlet pressure =0.1 MPa, compressor outlet pressure = 30 MPa, and liquefied NG temperature = -161.75 ºC, compressor efficiency of 0.8, and heat exchanger efficiency of 0.836. After substituting standard chemical potential and mole fraction of environmental species into equation (4) ($X_c = \mu_{CH_4} + 2\mu_{O_2} - \mu_{CO_2} - 2\mu_{H_2O}$) the chemical exergy of methane is obtained as 51.875 MJ/kg which is in between lower heating value and higher heating value of methane. *Fig. 3* shows this exergy analysis and destruction rate at each component of the cycle in a Sankey diagram.

Thermodynamic analysis demonstrates that 20% of the input exergy is utilized in the LNG plant itself and the remaining 80% is ready for shipment. Also, 1.6% of input exergy later could be retrieved (mainly for refrigeration purposes) in the regasification plant. The inherent amount of exergy destruction in the LNG export process was one of the initial motivations to examine the alternative use of NG supply domestically in HVAC and road transportation systems.

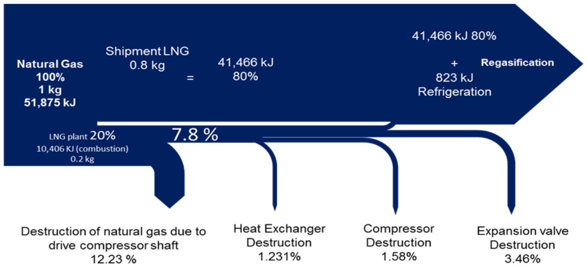

Figure 3. Exergy analysis of simple LNG system in a Sankey diagram

B. *Alternative HVAC system*

The exergy efficiency of a Vuilleumier heat pump [2] can be expressed as:

$$\eta_{ex} = \frac{X_{out}}{X_{in}} = \frac{Q_{Home}\left(1 - \frac{T_o}{T}\right)}{X_{in}} \tag{9}$$

where Q_{Home} is the supply heat to the room, T_o is the ambient temperature, T is the room temperature, and X_{in} is the chemical exergy of methane. Using equation (9), the exergic efficiency of a Vuilleumier heat pump (with the COP of 1.6) for temperature range of 0 to 25 ºC is found to be 13%. Comparing the exergic efficiency of a Vuilleumier heat pump with that of an electric baseboard heater (which is only 6% [12]) reveals the importance of using alternative HVAC systems. Also, equation (9) could be applied to determine the exergy efficiency of a heat pump with the COP in the range of 2.5-4, which gives efficiencies in the range of 19% to 33%.

The exergy efficiency of a NG electricity generation plant based on estimates [13] and [14] has a range of 40%-70% depending on the thermodynamic cycle. Furthermore, the electrical transmission efficiency from [7] is assumed to be in the range of 93% to 98%. Hence, we can estimate the conversion efficiency of a NG resource to heating use in an HVAC system. Fig 4 demonstrates this comparison between the studied systems. The Vuilleumier heat pump can be a better choice depending on the COP of the heat pump and electricity generation efficiency. Overall, baseboard electric heater has the lowest exergy efficiency.

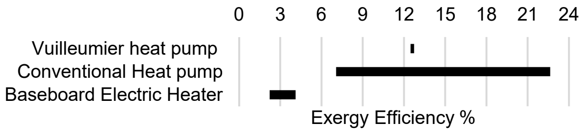

Figure 4. Comparing exergy efficency of alternative HVAC pathways based on NG feedstock.

C. *Alternative road transportation pathways*

For pathway analysis in the road transportation sector we proceed with a slightly different approach. Based on various literature sources, the exergy efficiency of different conversion processes (table (1)) are then inserted into equation (4). The result of this pathway analysis is shown in Fig 5.

TABLE I. EXERGY EFFICIENCY OF EACH PROCESS

Process	Exergy efficiency	Reference
FT Diesel & Gasoline production	0.62-0.69	[15]
NG Pipeline Transmission	0.99	[16]
NG electricity generation plant	0.4-0.7	[13], [14]
Diesel & Gasoline Engine	0.1-0.34	[17], [18]
CNG Compression	0.92-0.97	[7]
LNG Liquefaction	0.8[a]-0.956	[19]
H2 Reformer	0.5-0.62	[20]
Electricity Transmission	0.93-0.98	[7]
CNG & LNG Engine	0.25-0.35	[7]
Fuel Cell Engine	0.48-0.50	[7]
Battery Charging	0.72-0.9	[7]

[a] Liquefaction efficiency from section A

This result lends strong support to using NG to first generate electricity to charge the battery electric vehicle pathway. The most promising futuristic technology for NG electricity generation is the triple cycle, with reported efficiencies of 70%. Even adopting fuel cell vehicles could not increase the overall efficiency above 30%.

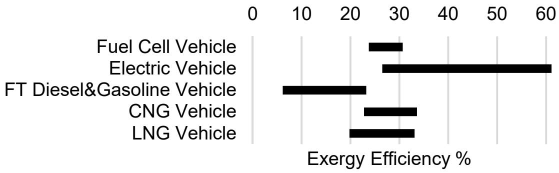

Figure 5. Comaprison of exergy efficency of alternative transportation pathways based on NG feedstock

V. CONCLUSIONS

There appears to be viable possibilities for using NG resources in the B.C. HVAC and transportation sectors. We have outlined some alternative pathways for BC NG supply to be employed domestically and introduced metrics to assess how this transition could actually occur over time. The final contribution of this research will be the integration of a wide range of perspectives from energy efficiency, economics and public policy to develop a framework in order to employ NG supply in the most optimal and sustainable ways. The unique part of the proposed work is in trying to answer the questions around how using the inexpensive NG supply in the current energy system will eventually navigate the B.C. economy and energy system towards future long term low carbon energy systems. Thus far, we demonstrated that the Vuilleumier heat pump and battery electric vehicles could be optimal options for building HVAC and transportation systems.

Future work will focus on road freight trucking where the fuel supply is dominated by diesel. Thus, NG can be an ideal solution for this sector because biofuel, hydrogen and plug-in-battery electric options might be not enter into this market for several decades. Furthermore, emissions from heavy-duty diesel vehicles account for approximately 8.5% of overall BC greenhouse gas (GHG) emissions [1]. Therefore, this sector is an important focus to examine alternative technologies to reduce GHG emissions. For example, the CIMS model can incorporate renewable fuels and other hybrid heavy-duty truck technologies. In this regards, pathway analysis in terms of exergy efficiency and alternative climate metrics should inform hybrid economic model in order to have a more precise policy recommendation framework.

REFERENCES

[1] B.C. Greenhouse Gas Emissions 2013. http://www2.gov.bc.ca/gov/content/environment/climate-change/reports-data/provincial-ghg-inventory-report-bc-s-pir.

[2] W. Goetzler, R. Zogg, J. Young, and C. Johnson. Energy savings potential and R&D opportunities for nonvapor-compression hvac technologies. Technical report, Navigant Consulting, Inc, 2014.

[3] Böhringer, C., & Rutherford, T. F. Combining top-down and bottom-up in energy policy analysis: A decomposition approach. Mannheim: ZEW, 2006.

[4] Murphy, R., & Jaccard, M. Energy efficiency and the cost of GHG abatement: A comparison of bottom-up and hybrid models for the US. *Energy Policy, 39*(11), pp. 7146-7155, 2011.

[5] M. Jaccard, R. Loulou, A. Kanudia, J. Nyboer, A. Bailie, M. Labriet, Methodological contrasts in costing greenhouse gas abatement policies: Optimization and simulation modeling of micro-economic effects in Canada, Operational Research, vol. 145(1), pp. 148-164, 2003.

[6] Adam P. Simpson. Decision Making in Energy: Advancing Technical, Environmental, and Economic Perspectives. PhD thesis, Stanford University, April 2010.

[7] Michael G. Waller and Eric D. Williams and Schuyler W. Matteson and Thomas A. Trabold. Current and theoretical maximum well-to-wheels exergy efficiency of options to power vehicles with natural gas. Applied Energy, vol. 127, pp. 55–63, 2014.

[8] IPCC, Climate Change 2007: Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

[9] Morgan R. Edwards and Jessika E. Trancik. Climate impacts of energy technologies depend on emissions timing. Nature Clim. Change, vol. 4(5), pp. 347–352, May 2014.

[10] Argonne National Laboratory. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, 2015. https://greet.es.anl.gov/

[11] M. J. Moran and H. N. Shapiro, Fundamentals of engineering thermodynamics, 5th ed, 2006.

[12] M. A. Rosen and C. A. Bulucea. Using exergy to understand and improve the efficiency of electrical power technologies. Entropy, vol. 11(4), pp. 820-835, 2009.

[13] E. Açıkkalp, H. Aras, A. Hepbasli, Advanced exergy analysis of an electricity-generating facility using natural gas, Energy Conversion and Management, vol. 82, pp.146–153, 2014.

[14] R. Z. Pass, C. F. Edwards, Exergy analysis of a solid-oxide fuel cell, gas turbine, steam turbine triple- cycle power plant, Proceedings of the ASME, 2012.

[15] Carmine L. Iandoli and Signe Kjelstrup, Exergy Analysis of a GTL Process Based on Low-Temperature Slurry F-T Reactor Technology with a Cobalt Catalyst, Energy & Fuels, vol. 21, pp. 2317-2324, 2007.

[16] M. Chaczykowski, A.J. Osiadacz, F.E. Uilhoorn, Exergy-based analysis of gas transmission system with application to Yamal-Europe pipeline, Applied Energy, vol. 88, pp. 2219–2230, 2011.

[17] G. Bourhis and P. Leduc, Energy and Exergy Balances for Modern Diesel and Gasoline Engines, Oil & Gas Science and Technology, Vol. 65, pp. 39-46, 2010.

[18] C. Sayin, M. Hosoz, M. Canakci, I. Kilicaslan, Energy and exergy analyses of a gasoline engine, Int Journal of Energy Research, 2006.

[19] A. B. Rian, H. Lie, I. S. Ertesvåg, Energy and Exergy an Analysis of Snøhvit - an LNG processing plant in Norway, NTNU, 2006.

[20] A. P. Simpsona, A. E. Lutzb, Exergy analysis of hydrogen production via steam methane reforming, Hydrogen Energy, vol. 32, pp.4811 – 4820, 2007.