

Long-Term Renewable Energy Generation Planning for Off-grid Remote Communities

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Electricity is widely seen as a flexible energy source that can potentially improve access to services and economic development in remote locations. Worldwide, there are 1.3 billion people without electricity access, out of which 950 million are not likely to be connected to the main grid in the foreseeable future. Furthermore, there is a population sector which solely relies on diesel-fuel for electricity generation; these communities have usually limited installed capacity, lack of operation flexibility, significantly high operating costs, and different operation characteristics involving multiple stakeholders. Incorporation of adequate Renewable Energy (RE) technologies can potentially reduce the energy deficit, addressing some of the aforementioned issues, such as requirement of increased installed capacity and reducing fuel consumption. In this thesis, the Long-Term Renewable Generation Planning (LTRGP) problem in Remote Communities (RCs) is tackled to address some of energy-access issues, based on a mathematical model that results in economic and technically-feasible RE deployment plans that consider current operating conditions, bringing benefits to the community.

Proper understanding of the energy situation in remote locations is an essential requirement for proposing RE deployments in Northern and Remote Communities (N&RCs). Hence, this thesis first presents the results of a Canada-wide survey regarding N&RCs. The resulting database is then used to shape the structure of the LTRGP model, as well as giving a reliable input baseline for the presented research. In addition to energy-related information, the database contains detailed time-series data for solar and wind-related resources, which are used as inputs to the proposed planning problem.

The first proposed approach to solving the LTRGP problem is based on understanding the current electricity generation structure in N&RCs, and adapt available RE planning tools accordingly. This work involves understanding the challenges of such RE projects by analyzing the current economic structure, capital costs, available natural resources, deployment, and Operation and Maintenance (O&M) issues. Based on this analysis, the thesis presents a planning model in HOMER, a currently available RE microgrid planning tool. The model is applied and demonstrated in a case study considering the northern Ontario community of Kasabonika Lake First Nation (KLFN), with which the University of Waterloo has had a strong collaboration for several years. The results show that RE technologies are close to breaking even under certain deployment conditions; however, low economic returns are obtained.

The second approach in this RE planning research is the development of an appropriate

LTRGP model considering the characteristics of RCs which cover their electricity demand using mainly Fuel-based Generators (FGs). From a non-technical viewpoint, the model considers the different RE operating frameworks, the current electricity customer types, and the involved stakeholders in remote locations. From a technical perspective, a mathematical model of a multiple-year RE planning model is proposed considering the technical and economic constraints related to such locations, some of which are not present in the grid-connected context. The resulting model is applied to the KLFN case and the results show that RE projects can be feasible for some funding alternatives. The results demonstrate that realistic RE community plans can be obtained with the proposed model, considering wind and solar energy generation equipment that is adequate for such remote locations and the current operating and tariff structure among the parties involved.

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Dedication

To my parents, Blanca and Mariano; my sister, Lissette; and niece, Luna.

To my grand father, Mariano.

To my girlfriend, Cox.

Table of Contents

List of Figures	xi
List of Tables	xiv
Abbreviations	xv
Nomenclature	xvii
1 Introduction	1
1.1 Motivation and Relevance	1
1.2 Literature Review	4
1.2.1 Renewable Energy in Canadian Isolated Microgrids	4
1.2.2 Renewable Energy Microgrids Planning Models	8
1.3 Research Objectives	12
1.4 Thesis Organization	14
2 Background	16
2.1 Renewable Energy Microgrids	16
2.1.1 Microgrids Benefits and Challenges	17
2.1.2 Microgrid Control	18
2.2 Distributed Energy Sources	20

2.2.1	Solar Photovoltaic (PV) Model	21
2.2.2	Wind Turbine Model	22
2.2.3	Energy Storage	25
2.3	Renewable Energy Planning Tools	27
2.4	Mathematical Modelling	29
2.4.1	Mixed-Integer Non-linear Programming (MINLP) Problems	29
2.4.2	MINLP Solution Techniques	30
2.5	Summary	32
3	Access to Electricity in Canada’s Northern and Remote Communities	33
3.1	Database Methodology and Challenges	33
3.1.1	Methodology	34
3.1.2	Challenges	35
3.2	Canadian Northern and Remote Communities (N&RCs)’ Grids and Microgrids	35
3.3	Electricity Generation	36
3.4	Electricity Demand and Fuel Consumption	42
3.5	Electricity Rates	43
3.6	Energy-related Issues	46
3.7	Wind and Solar Resources in N&RCs	47
3.7.1	Solar Irradiation Data	48
3.7.2	Wind Speed Data	48
3.8	Summary	48
4	Microgrid Renewable Energy (RE) Generation Planning Based on Existing Tools	52
4.1	Energy Status of Northern Ontario Remote Communities	52
4.1.1	Electricity Model Structure and Costs	54
4.1.2	Carbon Emissions and Environmental Issues	56

4.1.3	RE-based Microgrid Operating Issues	56
4.2	Mathematical Model	57
4.2.1	Wind and Solar Resources	58
4.2.2	Diesel and Battery Dispatch Strategy	59
4.3	RE Alternatives for Kasabonika Lake First Nation (KLFN)	61
4.3.1	The Community	61
4.3.2	RE Equipment Characteristics and Costs	62
4.3.3	RE Scenarios	63
4.3.4	Discussion	68
4.4	HOMER limitations	69
4.5	Summary	71
5	Mathematical Programming Approach for Microgrid RE Generation Planning	72
5.1	Electricity Rates and Subsidies	72
5.2	Planning Mathematical Model	73
5.2.1	Model Architecture	75
5.2.2	Stage I: Historical Data and Equipment Specifications	77
5.2.3	Stage II: Forecasts	78
5.2.4	Stage III: Generation Equipment Considerations	80
5.2.5	Stage IV: RE Long-term Planning	83
5.3	Case Study: Kasabonika Lake First Nation	90
5.3.1	Scenarios	91
5.3.2	Results	93
5.4	Summary	102

6 Summary and Future Work	104
6.1 Summary and Conclusions	104
6.2 Main Contributions	105
6.3 Future Work	106
References	108

List of Figures

1.1	Aerial view of Makkovik Inuit, Labrador, where an Fuel-based Generator (FG) facility is currently the sole alternative for electricity generation, Labrador (courtesy of Oliver Johnson).	3
1.2	Solar PV system installed at the remote Torngat Mountains National Park base camp, Labrador (photo courtesy of Oliver Johnson).	5
1.3	Small WTs with tilt-up towers installed at KLFN, Ontario.	6
2.1	Solar PV array output voltage with and without temperature effect.	22
2.2	Temperature impact on solar PV array output power variations.	23
2.3	Stall-controlled WT power output differences due to the air density/temperature effect.	26
2.4	Pitch-controlled WT power output differences due to the air density/temperature effect.	27
3.1	Classification of Canada's N&RCs based on electricity generation installed capacity.	37
3.2	Utilities operating in Canada's N&RCs.	38
3.3	N&RCs electrical equipment installed capacity by province and energy source.	39
3.4	Air-access is the only means of transportation available for some Remote Communities (RCs) during certain seasons of the year.	41
3.5	Fuel transportation to RCs is an expensive operation since in some locations most of the fuel is flown in (photo courtesy of Oliver Johnson).	41
3.6	Annual load profile examples for selected RCs across Canada.	42

3.7	Fuel consumption for electricity generation per province and territory. . . .	43
3.8	N&RCs' electricity rates by province and territory for (a) non-government residential, (b) non-government general services, (c) government residential, and (d) government general services.	45
3.9	Global Horizontal Irradiance (GHI) information for N&RCs.	49
3.10	Annual average wind speed at N&RCs.	50
4.1	Stakeholders' cash flow from electric generation activities.	55
4.2	Wind and solar capacity factors for Ontario's RCs.	60
4.3	Annual/daily power generation and RE contribution in low-penetration scenario.	66
4.4	Annual/daily power generation and RE contribution in medium-penetration scenario.	67
5.1	Mathematical model architecture.	76
5.2	Normal distribution fit example for annual solar irradiation averages for KLFN.	79
5.3	Normal distribution fit example for annual wind speed averages for KLFN.	79
5.4	Scenario 3. RE long-term plan: (a) deployment costs and (b) capacity.	95
5.5	Power output per generator type for Scenario 3 after all RE equipment has been deployed (June 23-25, 2020).	96
5.6	Cash-flow for Scenario 3.	96
5.7	Proposed RE deployment capacity per scenario: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.	98
5.8	Proposed annual RE contribution: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.	98
5.9	Proposed maximum RE penetration in one hour: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.	99

5.10	Discounted social welfare breakdown: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.	100
5.11	Internal Rate of Return (IRR) obtained per stakeholder and scenario: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.	101
5.12	External funding versus subsidy offset: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.	102

List of Tables

4.1	Electric energy supply status for Ontario's RCs.	53
4.2	Estimated installation costs of RE equipment at KLFN.	64
4.3	Summary table for KLFN low- and medium-RE-penetration scenarios. . .	70
5.1	RE operation schemes and customer types for remote communities	74
5.2	RE planning model parameters for the KLFN case study	92
5.3	KLFN case study parameter values.	93

Abbreviations

AANDC	Aboriginal Affairs and Northern Development Canada.
AER	Applicable Electricity Rate.
AFC	Avoided Fuel Cost.
AWEA	American Wind Energy Association.
CanWEA	Canadian Wind Energy Association.
CB	Capacity Building.
CF	Capacity Factor.
DC	Direct Current.
DER-CAM	Distributed Energy Resources Customer Adoption Model.
DG	Distributed Generator.
DIRECT	Dividing Rectangles.
DNI	Direct Normal Irradiance.
EMS	Energy Management System.
FG	Fuel-based Generator.
GA	Genetic Algorithm.
GAMS	General Algebraic Modeling System.
GHG	Greenhouse Gases.
GHI	Global Horizontal Irradiance.
HORCI	Hydro One Remote Communities Incorporated.
IEA	International Energy Agency.
IEC	International Electrotechnical Commission.
IRR	Internal Rate of Return.
KLFN	Kasabonika Lake First Nation.
LCOE	Levelized Cost of Energy.
LPSP	Loss of Power Supply Probability.
LRes	Load Restriction.

LTRGP	Long-Term Renewable Generation Planning.
MILP	Mixed Integer Linear Programming.
MINLP	Mixed-Integer Non-linear Programming.
MPP	Maximum Power Point.
N&RCs	Northern and Remote Communities.
NASA	National Aeronautical and Space Administration.
NM	Net-Metering.
NPV	Net Present Value.
NRCan	Natural Resources Canada.
O&M	Operation and Maintenance.
OPA	Ontario Power Authority.
PLC	Programmable Logic Controller.
PPA	Power Purchase Agreement.
PV	Photovoltaic.
RC	Remote Community.
RE	Renewable Energy.
RFI	Request for Information.
RFP	Request for Proposal.
RRRP	Rural or Remote Electricity Rate Protection.
SbC	Subsidized Customer.
SC	Self-Consumption.
TIMES	The Integrated MARKAL-EFOM System.
UbC	Unsubsidized Customer.
WT	Wind Turbine.

Nomenclature

System parameters

BLT_k	Bank loan term [years].
CD_i	Selling or savings electricity applicable rate for customer i [\$/kWh].
CPI	Customer Price Index.
CT_i	Binary value used for distinguishing between RE curtailment classes.
C_{BW}	Cost of battery wear [\$/kWh].
C_{FUEL}	Actual oil-based fuel price [\$/litre].
ELT_k	Operation lifetime for equipment k [years].
INC_i	External incentive rate for customer i [\$/kWh].
IRR_i^{\max}	Maximum IRR required for a feasible deployment plan [%].
IRR_i^{\min}	Minimum IRR required for a feasible deployment plan for customer i [%].
$P_{D_{i,t,h}}$	Customer i load on year t at hour h [kW].
$P_{D_{t,h}}$	Community demand on year t at hour h [kW].
$P_{FG_{BASE_{j,t,h}}}$	Required active power for baseline scenario produced by FG j on year t at hour h [kW].
$P_{REM_{k,g,t,h}}$	Active power output obtained for each equipment unit k combined with complementary unit g from the respective RE model on year t at hour h [kW].
$P_{REM_{k,t,h}}$	Active power output obtained for each equipment unit k from the respective RE model on year t at hour h [kW].
RC_{CAP_k}	Present capital cost for RE equipment k per installed capacity unit [\$/kW].
RC_{OM_k}	Present Operation and Maintenance (O&M) cost RE equipment k per installed capacity unit [\$/kW].
RD_i	Discount rate for customer i [%].
RP_t^{\min}	Rated power for the smallest nominal power FG operating on year t [kW].
RP_k	Nominal rated power for equipment k [kW].
RP_j	Nominal rated power for equipment j [kW].
α	Dispatch strategy reduced partial-load ratio limits.
β	Dispatch strategy increased partial-load ratio limits.
η_{RT}	Round-trip battery storage efficiency.
b_{CB}^{\max}	Maximum Capacity Building (CB) reduction percentage [%].
$b_{IC_t}^{\max}$	Maximum allowable RE installed capacity ratio with respect to the average annual load on year t .

b_{CBb}	Constant coefficient for CB linear equation.
b_{CBm}	Linear coefficient for capacity building linear equation.
b_{CBu}	Number of RE units to be installed to achieve maximum CB cost reduction.
b_{CEP}	In-hand capital contribution ratio available at the start of the project.
b_{CFP_t}	Percentage of the total fuel consumption supplied by the community to the utility on year t [%].
b_{D_i}	Customer i load ratio of the total community demand.
b_{EFP}	Project external funding ratio of the total project capital cost.
b_{OM_t}	Annual O&M variation due to technology change on year t .
d_{GS}^{\min}	Minimum operation load ratio for FGs.
$d_{GSLIM_{i,t}}$	FG operation limit at which RE is curtailed when reached [kW].
$d_{GS_{1,2}}$	Load ratio limit for generator switching condition.
d_{GSa_j}	Linear fuel consumption coefficient for diesel generator j [litre/kW].
d_{GSb_j}	Constant fuel consumption coefficient for diesel generator j [litre].
f_{BASE_t}	Fuel consumption baseline obtained from currently installed generation equipment on year t [litre/year].
$p_{j,t}^{\max}$	Maximum operation limit for FG j on year t .
$p_{j,t}^{\min}$	Minimum operation limit for FG j on year t .
r_B	Bank loan interest rate [%].
r_i	Inflation rate for the applicable electricity tariff for customer i [%].
r_{FR}	Percentage revenue obtained by the community from fuel sales for electricity generation [%].
$s_{j,t}$	Binary value to define if FG j is available for operation on year t .

Solar parameters

C_{PVINV_g}	Capital cost for solar inverter type g [\$/unit].
C_{PVOM_k}	O&M cost for PV equipment type k [\$/unit].
C_{PVU_k}	Capital cost per PV solar panel for equipment type k [\$/unit].
G	Global solar irradiation [kWh/m ² /day].
$I_{PVINV_g}^{\max}$	Maximum DC current rating for solar inverter type g [A_{dc}].
I_{0_k}	Leakage current for solar panel type k [V_{dc}].
I_{MP_k}	Maximum Power Point (MPP) nominal current for solar PV equipment type k [A_{dc}].
$I_{PV_{k,t,h}}$	DC current for solar PV array when using type k panels on year t at hour h [A_{dc}].

Ka_{PV}	Boltzmann constant [J/°K].
NS_k	Number of cells in series for solar PV panel type k .
PR	Solar PV performance ratio.
$P_{PVINV_g}^{nom}$	Nominal DC power for inverter type g [V_{dc}].
$P_{PV_{k,t,h}}$	DC power output of solar PV array using type k panels on year t at hour h [kW].
Rp_k	Parallel resistance for PV equipment type k [Ω].
Rs_k	Series resistance for PV equipment type k [Ω].
$TM_{t,h}$	Ambient temperature on year t at hour h [°K].
$V_{PVINV_g}^{max}$	Maximum DC voltage level for MPP tracking for inverter type g [V_{dc}].
$V_{PVINV_g}^{min}$	Minimum DC voltage level for MPP tracking for inverter type g [V_{dc}].
V_{MP_k}	MPP nominal voltage for PV equipment type k [V_{dc}].
$V_{PV_{k,t,h}}$	DC voltage for solar PV array when using type k panels on year t at hour h [A_{dc}].
a	Diode ideality constant.
q	Electron charge constant [C].

Wind parameters

A_{WD}	Scale parameter for Weibull distribution function.
C_{WTOM_k}	O&M cost for Wind Turbine (WT) type k [\$/unit].
$C_{WTTWR_{k,g}}$	Capital cost for tower type g for WT type k [\$/unit].
C_{WTU_k}	Capital cost per WT for equipment type k [\$/unit].
DF	WT de-rating factor.
PC_{WT_k}	Power curve for WT k [kW].
PC	WT power curve function.
$R_{SPECIFIC}$	Specific gas constant [J/(kg*K)].
$TM_{WT_k}^{max}$	Maximum operating temperature for WT type k [°K].
$TM_{WT_k}^{min}$	Minimum operating temperature for WT type k [°K].
WD	Weibull distribution function.
$\rho_{ACT_{t,h}}$	Actual air density on year t at hour h [kg/m ³].
ρ_{REF}	Reference air density [kg/m ³].
ht_{MS}	Wind speed measured height [m].
k_{WD}	Shape factor for Weibull distribution function.
p	Absolute pressure [Pa].
$v_{MS_{t,h}}$	Wind speed at measured height on year t at hour h [m/s].

Variables

$CB_{k,t}$	Cost reduction ratio due to capacity building for equipment type k on year t .
CL	Critical load for battery cycle charging [kW].
$CB_{L_{i,k,t}}$	Bank loan obtained for purchasing equipment type k for customer i on year t [\$].
$C_{BPMT_{i,k,t}}$	Amortization loan bank payments for equipment type k for customer i on year t [\$].
$C_{CAP_{i,k,t}}$	Capital cost of equipment k for customer i installed on year t [\$/kW].
$C_{CE_{i,k,t}}$	Initial capital expense contribution for equipment type k for customer i on year t [\$].
$C_{EF_{i,k,t}}$	External funding available for equipment type k for customer i on year t [\$].
$C_{OM_{i,k,t}}$	O&M cost of on-site equipment k for customer i on year t [\$/kW].
$C_{TEQ_{k,g}}$	Total Net Present Value (NPV) for equipment type k using complementary unit type g [\$].
$C_{i,t}$	Total capital and O&M of RE equipment for customer i on year t [\$/year].
$EOS_{i,k,t}$	Number of RE equipment units on-site for equipment k for customer i on year t .
$EQC_{k,t}$	Cumulative number of on-site equipment type k by year t .
IRR_i	IRR for RE operation for customer i [%].
$IS_{i,t}$	Income or saving obtained from RE for customer i on year t [\$/year].
$LC_{k,g}$	Levelized Cost of Energy (LCOE) for equipment type k using complementary unit type g [\$/kWh].
$LR_{i,t}$	Community loss opportunity cost from diesel sell due to RE generation for customer i on year t [\$/year].
$P_{DB_{i,t,h}}$	Active power difference between the available RE for customer i and the respective load on year t and hour h [kW].
$P_{FG_{j,t,h}}$	Required active power produced by FG j on year t at hour h [kW].
$P_{FG_{proj_{j,t,h}}}$	Required active power for RE projects scenarios by FG j on year t at hour h [kW].
$P_{FG_{t,h}}$	Required active power output from FG plant on year t at hour h [kW].
$P_{REa_{i,k,t,h}}$	Renewable active power available for customer i for equipment k on year t at hour h [kW].
$P_{REc_{i,k,t,h}}$	Renewable active power curtailed for customer i for equipment k on year t at hour h [kW].

$P_{REu_{i,k,t,h}}$	Renewable active power used to supply the load for customer i and equipment k on year t at hour h [kW].
$P_{WTO_{k,g,t,h}}$	WT power output before air density correction for WT type k using tower type g on year t at hour h [kW].
$P_{WTDC_{k,g,t,h}}$	WT power output after air density correction for WT type k using tower type g on year t at hour h [kW].
$P_{WT_{k,g,t,h}}$	WT power output after density and temperature corrections for WT type k using tower type g on year t at hour h [kW].
UC	FG unit commitment binary vector.
$W_{i,t}$	Social welfare for customer i on year t [\$/year].
f_{PROJ_t}	Fuel consumption obtained when considering RE projects on year t [litre/year].
$ht_{HUB_{k,g}}$	Hub height for WT type k using tower type g [m].
$v_{ADJ_{k,g,t,h}}$	Adjusted wind speed after air density correction for WT type k using tower type g on year t at hour h [m/s].
$v_{HUB_{k,g,t,h}}$	Wind speed at WT hub height for WT type k using tower type g on year t at hour h [m/s].
$x_{PVP_{k,g}}$	Integer variable for the number of solar PV panels connected in parallel for equipment type k when connected to inverter type g .
$x_{PVS_{k,g}}$	Integer variable for the number of solar PV panels connected in series for equipment type k when connected to inverter type g .
$x_{i,k,t}$	Integer variable for the number of RE units to be deployed for equipment type k for customer i on year t .
$y_{i,k,u,s}$	Auxiliary variable to represent on-site equipment k during its operation lifetime.
$z_{i,t,h}$	Renewable active power used ratio for customer i on year t at hour h .

Indices

- g Complementary equipment to be used with unit k ; $g = 1, \dots, G$.
- h Hours in a year; $h = 1, \dots, H$.
- i Subsidized unsubsidized or avoided fuel cost customer type; $i = 1, \dots, I$.
- j FG unit to be considered; $j = 1, \dots, J$.
- k Solar or wind technology equipment to be considered; $k = 1, \dots, K$.
- t Year; $t = 1, \dots, T$.

Chapter 1

Introduction

1.1 Motivation and Relevance

Access to energy in some of the world's Remote Communities (RCs) is still limited; these locations only have access to simple and inexpensive local energy sources such as biomass for cooking, and kerosene lamps or candles for lighting. The World Bank and the International Energy Agency (IEA) perceive this energy deficit as a major hurdle to achieve community development, access to health services, and clean water resources [1, 2]. In that context, electricity is a flexible modern energy source that is considered as one of the main driving forces to stimulate community economic development and access to basic services in remote locations [3]. Governments, private institutions, and non-government organizations have gradually recognized this fact and thus have established electrification programs at national and regional levels that aim to gradually electrify remote locations [4, 5].

The IEA estimates that 1.3 billion people worldwide have no access to electricity and that their interconnection to the existing electric grid is unfeasible in a 5-10 year time-frame. Most of this population (93%) is located in Africa (587 million) and Asia (675 million), while the remaining (7%) is distributed in Latin America (31 million), the Middle East (21 million), and developed countries [2]. The IEA estimates that by 2030, 30% (400 million) of this population can potentially be given access to the electrical grid, while the remaining 70% (950 million) can potentially be electrified with off-grid stand-alone or microgrid systems [5]. The configurations of such microgrids are strongly dependant on local economic, environmental, and social conditions; however, the possible configurations

can involve a combination of renewable (i.e., hydro, solar, wind, and biomass) and non-renewable energy sources (i.e., diesel-fuel and natural gas).

The population segment with no electricity access is only part of the remote energy problem, since nowadays some RCs produce electricity using only Fuel-based Generators (FGs). The authors in [6] estimates that diesel engines with a combined installed capacity of 10,000 MW are currently serving off-grid locations worldwide. Even though diesel-based generation in remote locations is associated with high energy costs, negative environmental impacts and electrical load restrictions, fossil fuels have been a reliable source of energy [3, 5]. On the other hand, these same FG issues create a high-cost baseline against which Renewable Energy (RE) projects can potentially compete, reducing the operation and environmental costs.

In Canada, approximately 200,000 people live in 280 communities across the country which, from an electrical perspective, are classified by Aboriginal Affairs and Northern Development Canada (AANDC) as off-grid communities, since they are not connected to the North American electric grid. These Northern and Remote Communities (N&RCs) currently satisfy their electricity needs mainly by using FGs, such as the one depicted in Figure 1.1, with some exceptions in which hydro is the primary energy source. For these communities, the electricity costs are higher than those for the rest of the country and vary significantly depending mainly on the communities' transportation access. For example, an all-year road access community can have an approximate electricity rate of \$0.45/kWh, while a mainly barge and/or air-access location can scale to \$0.80/kWh, and for Arctic locations the rate can range from \$1.50/kWh to \$2.50/kWh. For hydro-based generation, the rates in N&RCs range from \$0.15/kWh to \$0.40/kWh, depending on the northern location and installed capacity. In contrast, in the rest of Canada, the average electricity rates range from \$0.07/kWh to \$0.17/kWh, depending on the province given the significant difference in energy resources from province to province (in all chapters of this thesis, the dollar sign refers to Canadian dollars).

In addition to economic considerations, energy-resource awareness across utilities, institutions, and communities has increased over the years, which has resulted in increased attention to the issue of high electricity costs and the need to utilize RE in N&RCs [7]. Institutions have also been lobbying for a transition from the current energy framework to more comprehensive approaches that consider water, climate-change, socio-economic, health, and poverty issues (e.g., [8]). Finally, based on [9] and the experience gained during the preparation of this thesis, some RCs are genuinely interested in becoming more self-sufficient by increasing the use of their local energy resources.



Figure 1.1: Aerial view of Makkovik Inuit, Labrador, where an FG facility is currently the sole alternative for electricity generation, Labrador (courtesy of Oliver Johnson).

The energy-related challenges of N&RCs encompass economic, technical, social, and environmental issues that need to be collectively analyzed. From an economic perspective, the high energy rates are a direct consequence of the challenges that N&RCs currently deal with to supply electricity. Thus, Operation and Maintenance (O&M) of the energy generation and distribution infrastructure is expensive, since generally qualified technicians have to be flown in to conduct preventive and corrective maintenance. Furthermore, some N&RCs have specific rate adjustments on top of the base rates that fluctuate depending on the diesel-fuel cost. Road access for some N&RCs is limited to winter-roads for which serviceable life varies every year, and is subject to weight restriction depending on the ice conditions. From a technical perspective, energy generation technologies need to have a reasonably long lifetime while withstanding harsh operating conditions under minimum or locally-available maintenance personnel. From a social viewpoint, energy limitations can affect community development as the community electricity demand approaches current generation capacity limits. Finally, from an environmental perspective, diesel-based generation yields greenhouse-gas emissions regardless of the location; this issue can become

quite significant in light of the additional fuel transportation and community heating requirements faced by N&RCs. Therefore, from a planning perspective, all these issues need to be considered to properly determine the potential for deployment of RE in N&RCs, considering the installation and operating conditions in each community.

1.2 Literature Review

In this section, previous RE studies and projects developed in Canada’s N&RCs are mentioned to highlight the state-of-the-art in N&RCs microgrids, as well as to give a general perspective of the hurdles that RE deployment and operation practices still have to overcome to achieve larger RE penetration in these locations. In addition, an overview of the currently available microgrid planning models, their advantages, disadvantages, and relevance to this thesis, is also presented.

1.2.1 Renewable Energy in Canadian Isolated Microgrids

Over the last decades, there have been efforts from different stakeholders to address some of the above mentioned energy-related issues in N&RCs in Canada. Federal and provincial government agencies, utilities, non-profit institutions, companies, universities, and communities have individually, and in collaboration, tackled energy generation and demand challenges including energy efficiency, natural resources assessment, and RE alternatives. Natural Resources Canada (NRCan) has created a catalogue of the N&RCs’ energy requirements and supply [10]. The Pembina Institute has also conducted energy baseline assessment for several RCs in which the electrical and heating requirements are analyzed (e.g., [11]). In addition, several authors have done extensive research regarding wind measurement and wind power potential in RCs [12–14]. In [15], the author discusses inclusive project management frameworks that emphasize the need for strong partnerships among the involved stakeholders at all project stages. For several years, the Canadian Wind Energy Association (CanWEA) has lobbied for the adoption of a Wind Turbine (WT) incentive for off-grid projects, which is yet to be implemented [16]. In [17], the author expands on the idea of a RE policy for N&RCs by analyzing the energy efficiency potential, current RE barriers, and lessons learned from failed past incentive programs.

In recent years, there have been mainly pilot projects to further understand and assess the challenges of energy projects across N&RCs in Canada. A brief description of some of



Figure 1.2: Solar PV system installed at the remote Torngat Mountains National Park base camp, Labrador (photo courtesy of Oliver Johnson).

these projects follows:

- In British Columbia, a hydro-hydrogen-storage project was deployed in Bella Coola, proving the deployment capabilities of the technologies; the full potential seasonal savings of the project are being quantified. A 27 kW_p solar Photovoltaic (PV)-diesel system distributed across the community has been installed in Nemiah Valley, and 25% fuel costs reduction has been reported [18]. Recently, a smart-grid system has been installed in Hartley Bay to allow the community to explore alternatives for energy demand reduction [19].
- In Newfoundland and Labrador, the wind-diesel system installed in the reasonably accessible Ramea Island is an example of a system with 10-13% wind penetration (6x 65 kW WTs). The system is now being tested with hydrogen storage and further wind power (162 kW electrolyser, 5x 62.5 kW hydrogen engines, 3x 100 kW WTs) to increase the RE penetration level with a capital investment of \$9.7M [20–22]. Some remote northern stations have installed PV-diesel systems to supply power to base camps in Labrador (Figure 1.2).



Figure 1.3: Small WTs with tilt-up towers installed at KLFN, Ontario.

- In the Northwest Territories, there have been wind pre-feasibility studies and measurements in several RCs, as well as continuous installation of solar PV systems across the territory, currently accounting for 180 kW_p of solar PV systems [23]. Additionally, the Diavik diamond mine recently installed a 9.2 MW wind farm reducing the mine's annual fuel consumption by 3M litres [24].
- In Nunavut, significant work has been done to secure funding and assessments for the Iqaluit Hydro-Electric project, which in an initial stage will have a 10-14 MW installed capacity [25]. A few solar PV installations across the territory have been also deployed, as well as a 65 kW WT in Rankin Inlet [26].
- In Ontario, four WTs with a total capacity of 60 kW have been installed at KLFN, which is an initial step to understand the deployment of RE technologies in the RCs of the province (Figure 1.3); the University of Waterloo has been collaborating with Hatch Ltd. and the community to further understand the communities' energy requirements and challenges. Also, a PV-diesel system composed of 20 kW_p solar PV

and a 50kW diesel generator has been added to the microgrid system at Wawakapewin First Nation; the intention of the small diesel generator is to avoid running the larger units at low-load conditions [27]. Additionally, Hydro One Remote Communities Incorporated (HORCI), the utility serving approximately 60% of the RCs in the province, has created an incentive for customers to supply electricity with RE by implementing a modified feed-in-tariff program.

- In Quebec, two standalone wind-diesel systems have been recently planned to assess different technologies and RE penetration levels using flywheel systems: the Kangiqsualujjuaq project, with an 800 kW WT capacity and a 200 kW flywheel, and the Îles-de-la-Madeleine project, with 3x1 MW WT capacity and 1.5 MW flywheel. At this point, the first project has been stopped due to financial concerns and the latter is still under development (a detailed deployment status is not available at the moment) [28]. In addition, under the Innavik Hydro Electric project, a 7.5 MW run-of-the-river system, has been under assessment in Inukjuak [15].
- In the Yukon, there are two WTs with an installed capacity of 810 kW in Haeckel Hill, near Whitehorse [29], as well as a community-based wind farm project of 250 kW currently under development by the Kluane First Nation [30].

Even though most of the aforementioned projects refer to relatively small installed capacities compared to the respective total generation capacity, they are helping to better understand the deployment challenges of RE in the North, thus paving the way to larger deployments with higher RE contributions in the future.

In this thesis, some of the lessons learnt from the previous project are integrated into the proposed Long-Term Renewable Generation Planning (LTRGP) model. Various aspects considered in this research include the current deployment costs, operation frameworks, diesel-fuel generators dispatch strategies, and RE dispatch and curtailment approaches. The proposed model is based on input information and operation strategies obtained and currently implemented in RCs, extracted from the database for Canada's N&RCs created as part of this thesis. This information is essential to properly design the community LTRGP model, as well as to further understand the priorities and challenges in these remote locations.

1.2.2 Renewable Energy Microgrids Planning Models

Over the past couple of decades, academic, industrial and government sectors have demonstrated significant interest in optimal microgrid planning (e.g., [31, 32]). In this section, an overview of the relevant past work on RE planning for remote microgrids and on-grid energy planning is presented. The reviewed papers include a combination of conventional (e.g., FGs), non-conventional technologies (e.g., wind and solar), and storage systems (e.g., battery banks) that aim to expand the energy mix in remote microgrids while considering technical, environmental, and economic constraints at different levels of detail. The economic perspective is often the main priority and thus the related objective function seeks to minimize the total project cost. The environmental consideration is frequently represented by the reduction of Greenhouse Gases (GHG) emissions. The technical considerations are usually accounted for by using detailed generation equipment models, dispatch strategies, and power balance equations.

1.2.2.1 State-of-the-Art of Microgrid Planning Models

The authors in [33] summarize the state-of-the-art of optimal planning techniques for solar PV and wind energy systems in remote locations. The paper emphasizes that the optimal planning problem has widely focused on minimizing the project's lifetime cost while maintaining a certain energy availability criterion. This energy availability concept is frequently calculated using the Loss of Power Supply Probability (LPSP) concept, which is defined as the probability of failing to supply energy from the RE-based system over a period of time. In addition, the authors highlight that the optimization methodologies used over the years have covered both linear and non-linear approaches, solved with diverse methods, such as dynamic programming, Dividing Rectangles (DIRECT) optimization, graphical construction, and Genetic Algorithms (GAs). The paper also covers general equipment models used for solar PV and wind technologies, as well as a discussion on the sizing of FGs. However, the review fails to cover some specific issues related to RE deployment in remote locations, such as FGs current operating strategies, RE financing frameworks, and the different stakeholders involved in the process.

A thorough RE planning model review is presented in [34]. The authors cover the current bottom-up planning tools available (e.g., Distributed Energy Resources Customer Adoption Model (DER-CAM), The Integrated MARKAL-EFOM System (TIMES), and HOMER) highlighting their advantages and limitations. This paper presents a thorough

description of the previously-used optimization model framework, as well as solution techniques used over the years, indicating that Mixed Integer Linear Programming (MILP) and Mixed-Integer Non-linear Programming (MINLP) models are generally used for solving the RE sizing problem mainly due to equipment considerations. Furthermore, it discusses the use of metaheuristic methods, such as GA, simulated annealing, and particle swarm, for solving microgrid planning problems. The model proposed in this thesis can be included in this optimization framework trend.

The authors in [35] present a comprehensive approach to the RE planning in RCs by proposing a sustainability philosophy based on strong social agreements among the involved stakeholders. The authors discuss at a conceptual level that there must be trade-offs among the stakeholders to obtain optimal/feasible RE microgrid solutions. The paper also suggests a multi-objective optimization approach to balance the conflicting economic, technical, environmental, and social goals. Even though the ideas presented in the paper are important, the authors do not fully explain the model and no case studies or results are given. In this thesis, some of these concepts are further analyzed and implemented as part of the proposed LTRGP model, adding further levels of detail and presenting results based on a survey conducted for RCs in Ontario and other provinces and territories across the country.

1.2.2.2 Relevant Microgrid Mathematical Planning Models

The authors in [36] develop a methodology to size off-grid PV-wind-battery systems by considering historic site-specific meteorological data for the available solar and wind resources. The paper presents a dynamic model built in MATLAB and Simulink to assess the potential RE configurations based on energy availability and equipment downtime. The presented model evaluates the reliability of the system by using a boolean expression to determine if the proposed configuration meets the demand over a certain period of time, which can be considered a performance index. The paper does not elaborate on several assumptions regarding the availability of the natural resources information, and does not present a realistic economic evaluation to obtain the optimal sizing for the system; however, the paper discusses on current operating strategies for the considered RE equipment.

Reference [37] presents a deterministic approach to the RE planning optimization problem of a remote system. The author's approach is to economically evaluate all the possible RE combinations and solve the optimization problem by considering trade-offs among reliability, overall cost, and minimum use of FGs. The advantages of this approach are a

realistic planning model, and the realistic considerations regarding wind and solar information availability when assessing remote systems. Nevertheless, the model focuses on the economic aspects, and has a relatively low level of detail when considering the technical characteristics of the generation equipment and the dispatch strategy. In this thesis, some of the economic concepts used in [37] are implemented in the proposed LTRGP model.

The authors in [38, 39] propose a multi-objective probabilistic methodology to obtain the optimal equipment capacity of off-grid RE-diesel systems. The paper presents detailed device models for the RE and energy storage components, and uses a GA approach to obtain the optimal capacity of the different components, considering the nonlinear nature of the described problem. Most of the equipment parameters represented in the paper are relevant; however, some improvements can be made to consider commercial equipment characteristics, such as discrete variables for WT tower heights. More importantly, as discussed in [34], the multi-objective approach used in RE microgrid planning is dependant on the weight coefficients needed in the objective function.

The authors in [40, 41] present a comprehensive method for the RE microgrid planning problem by using a multi-objective optimization approach based on strong Pareto solutions using GAs. The conflicting objectives are the capital investment cost and GHGs, since in a RE-diesel-based project, the capital costs are likely to be lower while the GHGs are the highest. These papers present a suitable baseline for a realistic RE-diesel based system; however, the proposed algorithm does not consider certain issues related to remote installations. One of the main issues not accounted for is that the ownership of different generation equipment is diverse, and as a result the objective function is likely to increase in complexity and further depended on the assigned weights in the multi-objective problem.

The author in [42] addresses specifically the issue of sizing and planning for remote microgrids, focusing on the issue that most of the previously proposed methodologies have not considered the reactive power requirements of the RE system. The methodology includes single and multi-objective optimization approaches based on GA techniques. The model considers a significant level of technical detail; however, from the information available for the model, the method does not consider the same level of detail regarding economics and long-term feasibility. The research undertaken in this thesis addresses these issues.

1.2.2.3 Long-term Microgrid RE Planning Models

The authors in [43, 44] discuss the grid-connected microgrid planning problem for gas turbines under fuel-price fluctuations, focusing on the economic feasibility, since from their

perspective it is the major challenge, assuming that the technical feasibility of the system can be obtained under certain conditions. The optimization problem is modelled using an MILP model coded in General Algebraic Modeling System (GAMS) [45]; the main drawback of the model is that it considers only six “representative days” for the project evaluation process. The key point in these papers, which is considered in this thesis, is a multiple-year investment method to determine the optimal timing of the project’s capital expense. This concept is particularly useful, since for some RCs, the current on-site diesel cost and incentive conditions may not result in an economically feasible project at the present time; however, as these conditions change over time, the RE deployment perspective is likely to change.

The TIMES model is an energy planning tool designed to assess macro-scale energy systems and not microgrids described in [46]. However, this complex model contains several concepts that can be considered in microgrids and evidently in this thesis, such as the investment of multiple planning years, the Capacity Building (CB) as a result of continuous RE project deployment, equipment O&M, and energy output changes over the equipment operating lifetime. However, the tool is not designed to include technical details regarding energy equipment, which is required for the microgrid planning problem, as well as the current operating strategies of such remote microgrids.

1.2.2.4 RE Planning Models Applied to Canadian RCs

Since this thesis concentrates in remote microgrids in Canada, the following papers show examples of RE planning methodologies and case studies that have been applied to RCs in Canada. Thus, the authors in [47] focus on analyzing the economic benefit of deploying RE in remote locations. The paper briefly discusses the potential ownership alternatives for RE equipment in RCs, as well as briefly describing the technical constraints based on current operating strategies. However, in order to build up a case for economic feasibility, the paper considers certain cost reductions that could be difficult to realize from a practical point of view. Thus, the model assumes that cost and GHG emission reductions can result from RE deployment considering diesel fuel transportation costs and tax credits, respectively; these expenses and/or savings are not realistic when considering the low RE penetration case presented in the paper.

HOMER has been used in several RE planning case studies across Canada (e.g., [48,49]), as well as in Chapter 4 of this thesis. The diverse case studies in the literature present different levels of detail and post-processing of the information provided by HOMER.

However, as it is further discussed in Chapter 2, HOMER has certain limitations regarding the technical and economic evaluations of RE projects.

1.2.2.5 Summary

Summarizing the presented literature review, this thesis aims to in general address the economic and technical issues identified in the above-described methods, expanding the scope of RE planning to consider a long-term perspective that takes into account the current operating structures of RCs, and the community characteristics that have a direct impact on the feasibility of RE projects.

1.3 Research Objectives

This thesis proposes a novel LTRGP model for RCs where FGs are currently the main source of electric power generation. The model considers the current operating framework, as well as the technical and economic constraints of such locations, to propose RE project alternatives over a multiple-year time frame. The proposed methods are designed based on the currently-available information and structure of RCs; hence its implementation in community energy plans can be envisioned in the short-term [34]. Based on this research, the objectives of this thesis can be described as:

- Create a detailed database of the electricity generation and demand for nearly 300 N&RCs, including technical, economic, logistic, and environmental considerations, as well as detailed information regarding solar and wind-related resources, where information is available. This information is a critical input for the LTRGP model in this thesis.
- Analyze the created database to identify the challenges and opportunities with regard to electricity generation in Canada's N&RCs. The analysis includes understanding the current operating frameworks, as well as the community priorities in order to propose long-term RE plans that can be implemented within the current RC context.
- Propose alternatives for RE equipment deployment in northern Ontario based on the currently-available microgrid planning tools, estimating first the RE equipment potential output by calculating Capacity Factor (CF) values for wind and solar equipment. Second, determine potential feasible scenarios considering the significantly

high installation and O&M costs, and evaluate the economic and environmental effect of such projects.

- Develop a multiple-year RE planning model that can help RCs determine the feasibility of energy projects considering the characteristics of remote microgrids. The objective is to provide an RE plan which includes the RE equipment type and capacity that can be deployed, operation schemes under which RE units can operate, installation time-frame for the selected equipment, and RE equipment location for customers whose current load demand is known.

Based on the aforementioned objectives, this thesis concentrates on the development of a supply-side generation planning model covering technical, operational, economic, social, and environmental aspects of electricity generation with RE in RCs. The scope of the work presented below is based on the electricity related data and operation information for RCs:

- *Technical*: The technical analysis covers electrical energy balance of RE units at a 1-hour resolution level, as well as the current dispatch strategies of these technologies considering the technical characteristics and/or constraints of each type of generation equipment considered. It is assumed that the diesel generation deployment plan is managed by the utility and not the community. Also, demand response alternatives to reduce load peaks and the electricity grid are not considered in the proposed models, as a norm in these types of generation planning models.
- *Electricity operation structure*: The current electricity operation framework for RCs, including on-going and potential operation schemes under which RE equipment can be framed, is considered in detail in the presented work. This includes different types of subsidized and unsubsidized customers, as well as their electricity rates.
- *Economic*: The economic details related to RE project costs and associated income and/or savings, as well as the financing mechanisms and funding alternatives available to communities for such types of projects are considered in this research, including their change in value over a multi-year planning horizon. In addition, different funding alternatives from government and financial institutions are considered. However, the economic scope of this research does not include costs associated with grid upgrades that are not part of the assumed RE capital costs.
- *Social*: Some social aspects are embedded in the operational and economic parts of the planning model. Thus, the planning models are based on proposing RE projects

which are partially or fully owned by communities, so that the community accrues direct benefits and responsibilities associated with the projects. However, this research does not consider other social impacts of RE projects in RCs, such as RE-related employment generation and perception of RE within the community.

- *Environmental*: The current GHG emissions as a result of electricity generation using diesel generators is quantified, as well as the potential emission reduction from RE projects. Nevertheless, the model does not assign an economic value to such emissions since this might not bring immediate and direct economic benefit to the community. Other issues associated with the environmental footprint of the proposed solutions, such as diesel fuel leaks from storage and transportation, and GHG emissions related to fuel transportation, are not considered.

1.4 Thesis Organization

The rest of this thesis is organized as follows:

Chapter 2 presents a review of relevant background including a general overview of microgrids, highlighting their benefits and challenges; an overview of the current operating strategies in isolated microgrids is discussed. The mathematical models for the distributed energy sources considered in this research are presented next, including an overview of energy storage and its challenges in remote northern locations. The chapter also gives an overview of the current RE planning tools and discusses their applications. Finally, this chapter discusses the general MINLP problem and current solution techniques, since these are the type of optimization problems proposed in this thesis.

Chapter 3 presents a summary and analysis of the N&RCs information obtained for all provinces and territories in Canada. The main objective of this chapter is to highlight the energy issues in N&RCs, and the main challenges that future energy-related projects face in these locations. This chapter gives an estimate of the electrical generation installed capacity by energy source, focusing on fuel-oil consumption. An overview is also given of the diverse energy demand profiles and the electricity rates that apply to each type of client and the current subsidy frameworks, and a summary of the main challenges that current and future electrical generation projects face is presented. Finally, a set of the created Canada-wide maps displaying the solar irradiation and wind speed resources in N&RCs are provided.

Chapter 4 investigates RE alternatives to reduce diesel fuel dependency of electricity generation in Ontario's remote northern communities. The chapter discusses the challenges for RE projects in northern Ontario communities by analyzing the current economic structure, the high capital costs, the available natural resources, and the installation and operation complexity. Also, the RE planning problem for RCs based on HOMER is discussed, and an RE sizing case study based on the KLFN community is presented for low and medium RE penetration scenarios, presenting their various technical, economic, and environmental outcomes.

Chapter 5 proposes an LTRGP model for RCs, considering the characteristics of diesel-based RCs. The chapter initially analyzes the types of customers described in Chapter 3, and matches them to operating frameworks in which RE projects can be implemented. Then, the proposed mathematical model of the multiple-year LTRGP model, considering the related technical and economic constraints. Finally, a relevant case study applied to KLFN is presented, including scenarios for different parameters' values and analyzing their effect on the RE planning outcome.

Finally, Chapter 6 presents a summary of the thesis, highlighting its contributions and possible future research work.

Chapter 2

Background

In this chapter, a general overview of microgrids is presented, highlighting their benefits, challenges, and current operating strategies in isolated microgrids. The mathematical models of the distributed energy sources considered in the LTRGP model are presented considering their deployment in northern locations. An overview and considerations of energy storage systems in remote locations is also discussed, and current RE planning software tools and their applications are presented. Finally, the chapter explains the MINLP problem formulation and current solution techniques, which are relevant for the proposed LTRGP problem.

2.1 Renewable Energy Microgrids

The microgrid concept was introduced in [50], and can be defined as a group of loads and Distributed Generators (DGs), seen as a single controllable system that can be operated in parallel with the electric grid or as an electric island [51, 52]. In the last two decades, the electricity sector has started to consider a slight change in their operation strategy from a centralized to a decentralized approach in which microgrids and DGs slowly permeate the electric system [53, 54]. In this context, microgrids are now widely envisioned as part of the distribution system, due to the existing economic, technical, and environmental conditions [52, 55]. These on-grid microgrids are regarded as being able to disconnect and operate in island mode, which in the case of a remote microgrid is the sole operating approach. Therefore, the rest of this section concentrates on discussing the island-mode microgrid operating characteristics, benefits, and challenges as these relate to this thesis.

Microgrid DGs can include a wide range of technologies such as internal combustion engines, gas turbines, microturbines, photovoltaic systems, fuel cells, and wind power conversion systems [52]. Their integration needs to be properly planned, since the indiscriminate application of individual sources can cause significant problems within the system [52, 56]; hence, an RE planning strategy needs to consider the on-going benefits and limitations that individual equipment and the system have to face while operating in a remote environment.

2.1.1 Microgrids Benefits and Challenges

RE microgrid deployment in remote locations has potential economic, technical, and environmental benefits. The following are the main advantages:

- *Higher efficiency and reduced electricity cost:* DGs can be located close to the load, resulting in a reduction of distribution system losses [53, 57, 58]. However, the greater benefit can potentially come from reducing the time that diesel generators run at partial loads or simply avoiding starting them up. As it is discussed in this thesis, fuel-consumption reduction and its effect on the cost that customers pay for electricity in RCs is one of the major drivers for RE implementation in such locations [58], assuming that the proper agreements and operating frameworks are present.
- *GHG emission reduction:* As a direct consequence of diesel-fuel displacement, RE sources in a microgrid can result in reduction of GHG emissions [51]; however, the GHG reduction level is highly dependent on the microgrid configuration and control strategy.
- *Peak shaving:* DG units can potentially help with peak shavings [59], as well as improving the reliability of the system [60], which could potentially also help relieve load restrictions in RCs.

The potential benefits of microgrids can only be assured if the following challenges are overcome:

- *Energy management:* RE planning for isolated microgrids needs to consider energy issues such as supply and demand balancing, spinning reserves allocation, DG control, and variability of non-dispatchable energy sources. In addition, a microgrid has to deal with voltage and frequency regulation, power quality, bidirectional power flows,

low-inertia systems, and unbalanced loads [53, 59, 61, 62]. This thesis addresses some of these issues and their relevance to the LTRGP problem.

- *Standardization*: Microgrid implementation requires extensive custom engineering which can be seen as a drawback and a motivation for developing microgrid standards [52].
- *Ownership*: A microgrid will have different operating strategies depending on the number of stakeholders involved in the system. If the microgrid has a single owner, the overall system cost will likely be the objective function. However, if the DGs are owned by different stakeholders, the units will have individual objectives that are likely to conflict, impacting the development of optimal dispatch strategies [59]. As further described in the next chapters of this thesis, different ownership frameworks of the generation equipment is an important issue in remote microgrids, since different stakeholders may have different incentives to pursue RE projects.
- *Incentives, subsidies, and regulations*: Incentives and regulations for the installation and operation of remote RE microgrids are still in their early stages of development; there is a lack of experience with regulation and subsidies [53]. In some RCs, an incentive and/or energy subsidy is most likely to bring the operating costs down to the level that the community can afford, as it is discussed in Chapter 3 of this thesis.
- *Risk-adverse utilities*: Utilities are known for being risk/change adverse, arguing for further technology maturity before deployment [59]. Nevertheless, as it is later described in this thesis to certain extent, RE technologies can still be implemented in RCs without changing their current operating rules.
- *Communication and protection*: The protection scheme and the local/remote communication of the different DGs are important aspects when deploying and operating an RE isolated microgrid [51, 59, 62].

2.1.2 Microgrid Control

Microgrid control approaches are still under development; however, at a high level, several authors have agreed on some basic principles and hierarchical control structures. First, the microgrid control principles can be classified as having a centralized or decentralized approach [62]. The centralized approach controls the microgrid energy management for all

DG units at a single location; this allows for an overall optimal system strategy. In contrast, the decentralized approach gives individual DGs more operation flexibility where each unit can likely operate at its optimal level [63]; this is the case when multiple DG ownership schemes exist. Second, authors have agreed on a hierarchical structure that divides the microgrid tasks into three control levels, i.e., primary, secondary, and tertiary [61, 62, 64]. The primary control is set at the device-level and its objective is to adjust the equipment-related parameters (e.g., voltage and frequency droop control). The secondary control, also known as the Energy Management System (EMS), rests above the device-level control to supervise the overall microgrid operation; this control is responsible for the economic energy dispatch and unit commitment problem. The tertiary control is the highest control level and is used to coordinate the interaction of the main grid and several microgrids; the tertiary control is not directly applicable to remote microgrids.

DGs can be further classified as units that can be directly connected to the microgrid, and units that require a power electronic interface for their connection [65]. Examples for direct-connect units are rotary units, such as internal combustion engines or hydro turbines connected to a synchronous generator, while power electronics-dependent equipment includes solar PV panels, fuel cells, and battery banks. Direct-connect units are generally used as voltage and frequency references in a microgrid, since they are usually the highest capacity units. Power electronics-dependent units provide a flexible interconnection to the microgrid since the converter can adjust the characteristics of the delivered power based on a given control strategy. This classification is relevant for the proposed research since the operating strategy will highly depend on the type of DGs and their operation characteristics.

In [61], the authors discuss microgrid control strategies such as droop control, inverter mode control, primary energy source control, reverse droop control, and autonomous control. Droop controls emulate the operation of a rotating generator in a conventional grid, and aims to adjust the active and reactive power flows by making them a function of the change in frequency and voltage, respectively [52, 53, 59, 62, 65–67]. Inverter control mode is based on a voltage-source inverter that controls the injected voltage magnitude and phase which determines the active and reactive power flow [51, 65]. Primary energy source control relies on a the synchronous generator of a diesel-based or hydro system [65]. The reverse droop control was proposed due to the resistive nature of the distribution low-voltage network, and consists of a direct relationship between frequency and reactive power, and voltage and active power. Finally, an autonomous microgrid strategy considers the integration of energy storage systems to convert non-dispatchable units into pseudo-dispatchable

units. Even though the time-window where these strategies operate is shorter than those in the long-term microgrid operating strategies relevant to the proposed research, these issues will have to be assessed for their impact on the RE planning phase.

As it is further described in Chapters 3 to 5, the current operation of the FG units in RCs is relatively simple, due to the lack of flexibility and dispatch strategy alternatives; however, there are still challenges related to voltage and frequency regulation [68]. In general, two major dispatch strategies have been found in isolated FG plants: single-unit dispatch and parallel dispatch. Evidently, the single-unit operation strategy aims to cover the total community load with one unit under normal operating conditions. If a generator switch is required based on the pre-determined control set-points, FG units operate in parallel for only a few minutes to allow for the load to be transferred between units. In the case of parallel unit dispatch, there are mainly two widely used alternatives: droop and isochronous control mode [68, 69]. Droop control and voltage regulation provide adequate load sharing capabilities among the FGs given that the units can be set to operate at the same power output; typically diesel generator droop setting for voltage and frequency ranges from 3%-5% from no load to full load. In contrast, isochronous mode is an active control system that shares the load among the FGs by assigning proportionally equal load when compared to the rated capacity of each generator; thus, control signals are sent to each FG unit to set its fuel and excitation system accordingly. In isochronous mode, the FG are set to keep constant voltage and frequency, as well as maintaining communications to allow for power sharing among the units. From the available information obtained for RCs communities in Canada (see Chapter 3), isochronous control seems to be the preferred strategy.

2.2 Distributed Energy Sources

For the proposed RE planning model, both solar PV and WT alternatives are mainly considered for isolated northern RCs. Hence, appropriate equipment models need to be included, which integrate temperature compensation to adjust renewable power outputs. In this section, these models are discussed, as well as a comparison of the obtained outputs with and without temperature compensation. In addition, an overview of energy storage for RCs is provided, which highlights the challenges still to overcome to deploy such technology in remote locations. It is important to note that hydro power was not considered as part of this research, given the limited availability of detailed information on hydro resources in RCs [15].

2.2.1 Solar PV Model

Solar PV has been a preferred option for remote stand-alone and RE microgrid systems due to its modularity, simple installation, and reduced cost trends [5, 6]. Solar resources have an additional advantage over other non-dispatchable sources, such as wind energy, since the expected energy output is more predictable than a WT power output, as analyzed in Chapter 5. Furthermore, solar PV can be an alternative for remote microgrids even in remote northern locations, where the average solar irradiation is low, due to the technology's decreasing-cost trend, transportation modularity, simple installation, and low maintenance costs.

In Canada, the solar PV output power model for RCs needs to consider the wide temperature range that the solar PV modules have to experience in such northern locations throughout the year. Hence, the equation with temperature compensations for the solar PV equipment used in this research is given by [70]:

$$P_{PV_{k,t,h}} = V_{MP_k} \left\{ I_{PV_{k,t,h}} - I_{0_k} \left[\exp \left(\frac{q}{K a_{PV}} \frac{V_{MP_k} + R_{S_k} I_{MP_k}}{T M_{t,h}} \right) - 1 \right] - \frac{V_{MP_k} + R_{S_k} I_{MP_k}}{R_{p_k}} \right\} \quad (2.1)$$

where V_{MP_k} is the Maximum Power Point (MPP) nominal voltage for PV equipment type k ; $I_{PV_{k,t,h}}$ is the Direct Current (DC) current in year t at hour h for equipment type k ; I_{0_k} is the leakage current solar panel type k ; q is the electron charge constant; $K a_{PV}$ is the Boltzmann constant; $T M_{t,h}$ is the ambient temperature on year t at hour h ; R_{S_k} is the series resistance for equipment type k ; I_{MP_k} is the MPP nominal current for equipment type k ; a is the diode ideality constant; $N S_k$ is the number of cells in series for type k ; and R_{p_k} is the shunt resistance for equipment type k .

In order to verify the extent of the temperature effect on voltage and power output effect in northern locations, this model was implemented considering the datasheet information for a 16 solar PV-module string using Kyocera KD230GX-LPB PV panels (230 kW_p), which are available in Canada. The temperature and solar irradiation time-series correspond to the northern Ontario community of KLFN which is located at 53°N, where the hourly average temperatures range from -26°C to 31°C throughout the year. Figures 2.1 and 2.2 show the results for the solar PV model when exposed to the available average hourly time-series data for one-year, and compare the respective outputs with and without the temperature effect. The DC voltage output exhibits significant differences when the

temperature effect is considered; the temperature-corrected DC voltage peak output is approximately 20% higher than the non-corrected data. Similarly, the annual energy output for the temperature-corrected data is roughly 4% higher than the non-corrected data. This temperature effect is further considered in this thesis in the LTRGP model described in Chapter 5, since this temperature-effect has an impact on the solar PV array sizing step.

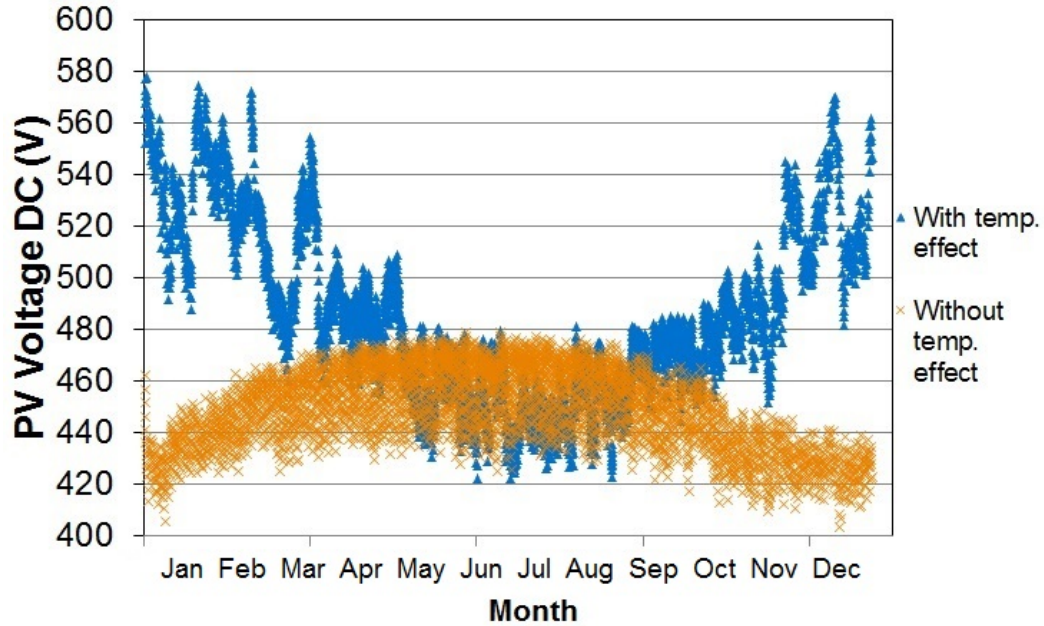


Figure 2.1: Solar PV array output voltage with and without temperature effect.

2.2.2 Wind Turbine Model

Large-scale wind turbines are widely installed in several parts of the world and have now a considerable impact on the electric grid [71]. The technology of large wind turbines has matured to the level that the design and performance can meet standards and certifications [72], but this has not been the case for small WTs (<100 kW), which have approximately 400 types and 230 manufacturers [73]. However, organizations such as the American Wind Energy Association (AWEA) have lately established formal certification processes based on International Electrotechnical Commission (IEC) standards for small WTs [72, 74]. Following these IEC standards, this thesis uses the wind energy equations

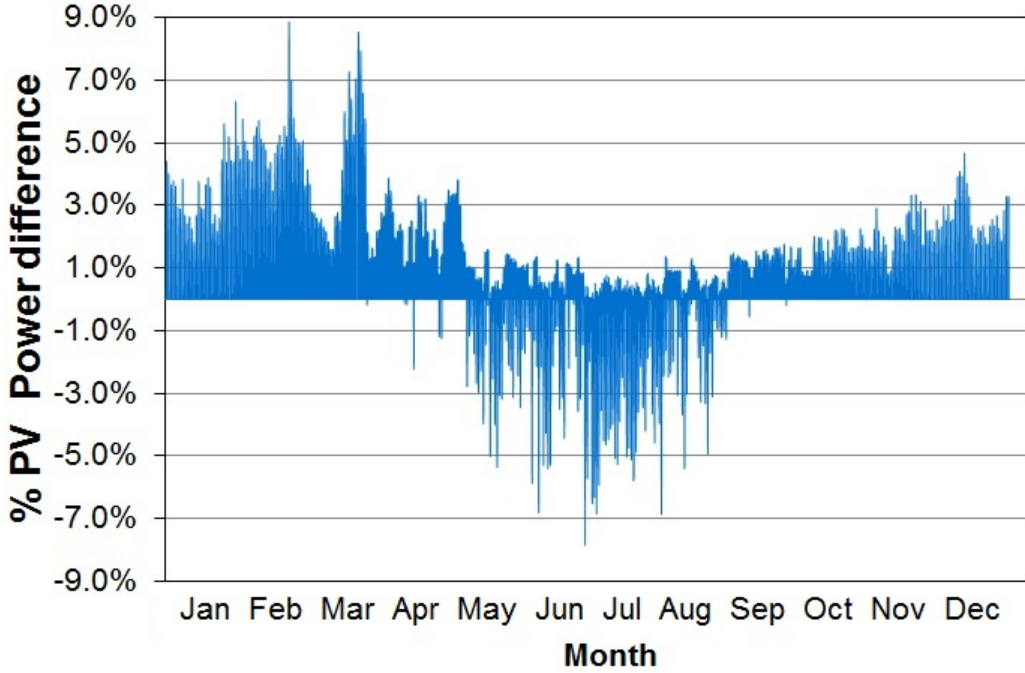


Figure 2.2: Temperature impact on solar PV array output power variations.

presented in [72] to calculate the WT power output, while considering aspects such as temperature correction and WT blade control systems.

The initial step in calculating the WT output is to adjust the wind speed data from the measured height to the expected WT hub height; this conversion is commonly performed using [72]:

$$v_{HUB_{k,g,t,h}} = v_{MS_{t,h}} \left(\frac{ht_{HUB_{k,g}}}{ht_{MS}} \right)^\alpha \quad (2.2)$$

where $v_{MS_{t,h}}$ is the wind speed at measured height; $ht_{HUB_{k,g}}$ is the expected WT hub height; ht_{MS} is the measured height; and α is the terrain surface roughness coefficient. With some exceptions, in RCs, there is currently no on-site wind monitoring equipment that can be used to calculate the expected WT power output. However, as it is described in Chapter 3, meteorological models are available which can give an approximation of the expected wind speed at different heights.

For horizontal-axis small WTs, there are basically two rotor speed control strategies:

stall and pitch-controlled systems. Stall-controlled WTs rely on a purely mechanical system to change the angle of the rotor-axis according to the wind direction. At high wind speeds, the stall-controlled system prevents the rotor from over-speeding, which could result in mechanical damage and/or fatigue over time. In general, the power output of stall-controlled WTs decreases significantly after the WT nominal wind speed is reached. In contrast, pitch-controlled WT have active control systems that adjust the orientation of the blades in the WT to maintain a close-to-optimal angle and rotor speed. In general, the power output of pitch-controlled WTs is maintained constant after the WT nominal wind speed is reached, and continues until the cut-off speed is reached. For the WT mathematical model, the required WT power output calculation needs to be corrected based on the blade control system and the air density/temperature variations at the location. Thus, the following equation aims to correct the expected WT power output for a stall-controlled WT by accounting for the air density change [75]:

$$P_{WTDC_{k,g,t,h}} = P_{WT0_{k,g,t,h}} \left(\frac{\rho_{ACT_{t,h}}}{\rho_{REF}} \right) \quad (2.3)$$

where

$$P_{WT0_{k,g,t,h}} = f(PC_{WT_k}, v_{HUB_{k,g,t,h}}) \quad (2.4)$$

$$\rho_{ACT_{t,h}} = \frac{p}{R_{SPECIFIC}(TM_{t,h} + 273.15)} \quad (2.5)$$

and PC_{WT_k} is the WT power curve; p is the absolute air pressure; $R_{SPECIFIC}$ is the specific gas constant for dry air; and ρ_{REF} the reference air density value.

Pitch-controlled WTs need to be also corrected for air density/temperature variations; however, due to the active control system, the effect is not the same as that for stalled-controlled WT. The power output equation for the pitch-controlled WT is given by [75]:

$$P_{WTDC_{k,g,t,h}} = f(PC_{WT_k}, v_{ADJ_{k,g,t,h}}) \quad (2.6)$$

where

$$v_{ADJ_{k,g,t,h}} = v_{HUB_{k,g,t,h}} \left(\frac{\rho_{ACT_{t,h}}}{\rho_{REF}} \right)^{\frac{1}{3}} \quad (2.7)$$

In order to verify the extent of temperature compensation effect on the output power in northern locations, the WT model for both blade control systems is implemented using the respective WT models. The stall-controlled WT considered here is the 50 kW Endurance E-3120 [76]; the nominal rated power and size of the E-3120 turbine makes it feasible to transport to a remote Ontario community over the current winter road restrictions. The pitch-controlled WT considered is the 600 kW Vestas V47 turbine [77]; these turbines tend to have a higher nominal rated power and require further logistic considerations, but this WT has been successfully deployed in the Yukon at a relatively more accessible location [78]. The temperature and wind speed time-series correspond to the northern Ontario community of Fort Severn located at approximately 56°N, which is one of the RCs in the province with higher wind energy potential. Figures 2.3 and 2.4 show the results for WT output power where the available average hourly time-series data for one year is applied to the model, and present the comparison between the respective outputs with and without the air density/temperature effect. In both cases, due to the increase in air density as a result of the low temperatures experienced throughout the year at Fort Severn, the energy output is higher. For this example, the annual energy output for the stall and pitch-controlled WT increases by 6.7% and 4.6%, respectively. From a planning perspective, this difference can be considerable when defining the type of WT to deploy.

2.2.3 Energy Storage

The objective of an energy storage system in a microgrid is to ensure balance of power in the system by compensating for the variability of intermittent RE sources and loads, as well as to increase the RE penetration in the system. Depending on the objective of the storage system and geographical, technical, and economic conditions, there are several energy storage alternatives, each with its own benefits and challenges [79]. For example, in the case of remote pilot-project microgrids, lead-acid battery banks have been one of the most commonly-used energy storage devices used to increase RE penetration, mainly due to their higher energy conversion efficiency and relatively low capital cost [80]. Furthermore in the case of short-term storage options such as flywheels, some projects have been implemented in remote parts of the world and, as previously mentioned; thus, there are projects assessing wind-diesel-flywheel systems in RCs in Quebec [28, 81].

From a RE planning perspective, long-term energy storage in RCs can further decrease diesel-fuel dependency, and allow for further microgrid operation flexibility. In the case of low RE penetration levels, storage systems are not required since the system considers

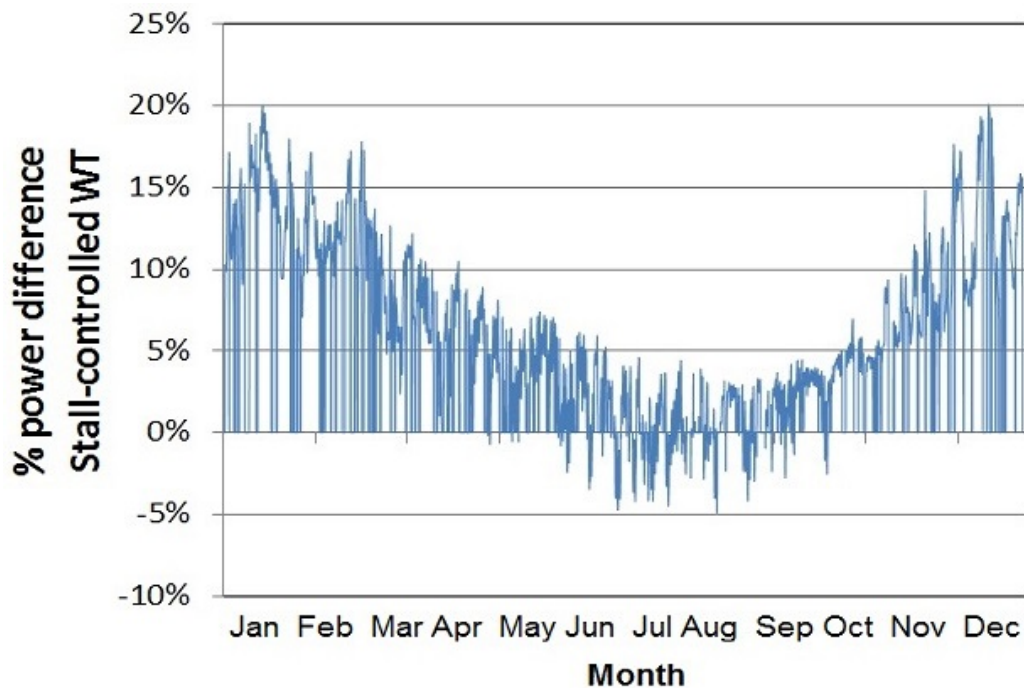


Figure 2.3: Stall-controlled WT power output differences due to the air density/temperature effect.

the RE contribution as a negative load. However, for medium and high RE penetration levels, storage energy systems are required to avoid operation problems within the grid. It should be noted that technologies such as battery banks still have significant technical and economic challenges before commercial deployment can be expected in remote locations. From an economic perspective, due to their current capital and O&M costs, the required storage equipment and deployment costs do not necessarily decrease the overall cost of energy [82]; this is a more significant issue in remote locations [28]. From a technical perspective, battery banks in Canada’s RCs also require further research regarding thermal management and operating lifetime.

In this thesis, energy storage is considered in Chapter 4 to assess the feasibility of a RE medium-penetration system in a remote community, without including the thermal management problem. The results obtained in the chapter are in line with those presented in [82], where the resulting overall energy cost shows a limited change when an energy storage system is considered. In Chapter 5, the LTRGP model presented does not consider energy storage alternatives since, as just described, the technology is still not at a point

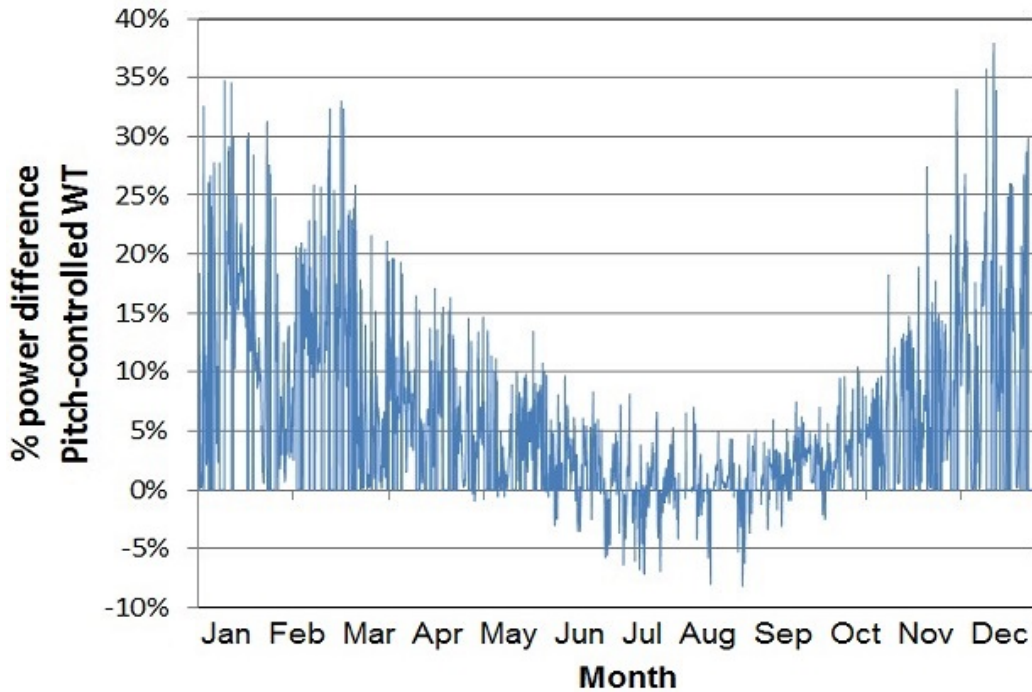


Figure 2.4: Pitch-controlled WT power output differences due to the air density/temperature effect.

where it can be economically feasible to deploy across RCs, specially in Canada, where the range of temperature variations throughout the year is significant, thus having a negative effect on the operating lifetime of the battery bank.

2.3 Renewable Energy Planning Tools

Microgrid and RE project sizing tools are available. The level of detail of these tools varies depending on the end-use and, as analyzed in [34], no single tool can be used for all aspects of the microgrid planning problem, with some tools being complementary among each other. The following is a summary of the tools assessed and their relevance to the RE planning problem described in this thesis:

- *DER-CAM*: This software considers a comprehensive economic and environmental model that can be used for determining the minimum cost equipment configuration

for a microgrid [83]. DER-CAM is able to handle different energy sources and services (e.g., electricity and heat), which as a result gives a full energy-picture for a given microgrid. However, multiple-year investment, project funding alternatives, and CB advantages in installation and O&M costs are not considered, which as it is discussed in Chapter 5, are important considerations for long-term energy planning.

- *ExploRA and OPERA*: Hydro-Québec is currently developing this software to plan and analyze microgrids with certain considerations for RCs in Canada; however, a version of this software is not yet available for assessment [28].
- *HOGA*: This program is one of the most recently developed software tools available for microgrid planning optimization, and is based on a multi-objective GA approach [84]. This tool has significant flexibility to combine different energy sources and evaluate operating strategies that impact the expected battery-bank lifetime. The software is useful due to its extensive technical details regarding the equipment models and operating strategy; however, the economic assessment is limited, only referring to the equipment cost and not including detailed financial feasibility.
- *HOMER*: This tool is likely the most widely-used software for planning RE-based isolated microgrids [32]. The software has gone through numerous upgrades and is able to deal simultaneously with diverse energy generation and storage technologies. HOMER has certain drawbacks that the user should consider, such as single Net Present Value (NPV) criteria for project evaluation, no detailed consideration of the technical feasibility of the resulting options, and lack of flexibility to post-process the obtained configurations. The software has been used for modelling on-grid and off-grid systems located across the world, including the assessment of the wind energy potential in RCs in Canada [12, 85–87]. This tool is used in this thesis to obtain the results presented in Chapter 4.
- *Hybrid2*: This software is one of the pioneering simulation software tools for RE hybrid system analysis [88]. The package can combine solar PV, wind, storage, and diesel technologies with a high-degree of technical detail, and supports various operating strategies. Inputting data to the program is relatively straightforward; however, the output is cumbersome and difficult to analyze. Improvements to this software were recently announced, but the new version version is not available yet.
- *RETScreen*: This tool is an Excel-based free-of-charge program developed by NR-Can for the high-level evaluation of RE and energy efficiency projects [31]. The

program performs dimensioning calculations to assess, from an economic and environmental perspective, the project’s pre-feasibility without extensive technical details. RETScreen includes a comprehensive solar irradiation and wind speed database that eases project assessment and presents a user-friendly interface. The program has been widely used for initial RE project assessment and has also been used to analyze RE projects in Canadian remote locations (e.g., [89]). The disadvantages of this tool are its limited energy source combination capabilities, rigid system architectures, and lack of alternatives for operating strategies; nevertheless, the software can be used to quickly obtain a preliminary plan.

- *TIMES*: This energy planning tool is designed to assess macro-scale energy systems (e.g., city and/or country-wide) and not specifically for microgrids [46]. The tool does not contain technical details regarding the energy equipment required for microgrid planning; however its multiple-year economic concepts and long-term planning approach are used in this thesis to define certain sections of the economic assessment of the LTRGP model presented in Chapter 5.

2.4 Mathematical Modelling

The RE planning problem requires a selection process involving potential RE sizing alternatives and, in the case of this research, the timings of such deployments. Hence in most cases, the mathematical modelling is based on optimization problems with their relevant constraints. As it is further described in Chapter 5, the model proposed here results in a MINLP problem. The mixed-integer component is the result of considering RE equipment units that can be deployed at remote locations, while the non-linear component is a result of some of the economic constraints considered as part of the feasibility criteria. Thus, this section gives an overview of the MINLP problem and related solution techniques.

2.4.1 MINLP Problems

Most engineering problems require the use of discrete and, in some cases, nonlinear models to closely represent a system. In optimization terms, this leads to MINLP problems that

can be generally defined as [90]:

$$\begin{aligned}
 \min \quad & f(x), \\
 \text{subject to} \quad & c(x) \leq 0, \\
 & g(x) = 0, \\
 & lb \leq c(x) \leq ub, \\
 & x \in X, \\
 & x_i \in \mathbb{Z} \quad \forall \quad i \in I
 \end{aligned} \tag{2.8}$$

where $c(x)$ and $g(x)$ represent the inequality and equality constraints, respectively; lb and ub are the respective lower and upper limit constraints; and $I \subseteq \{1, \dots, n\}$ is the index set of the integer variables.

The complexity of such problems arises from having to deal with discrete variables and the non-linear nature of the objective function and/or constraints. The following section describes some of the available techniques to solve these types of optimization problems.

2.4.2 MINLP Solution Techniques

Solving the MINLP problem can result in local minima that could be significantly higher than the desired global minimum. Depending on the type of problem, certain optimization solving techniques can get stuck in this type of solution. Hence, in some cases, a further search is required to increase the likeliness of obtaining a solution closer to the global optimum. There are several optimization problem solving methodologies that can help improve the expected suboptimal solution for a given MINLP problem. The following is a list of some of the available methods used to solve this type of optimization problem:

- *Multistart and Clustering Methods*: The Multistart optimization method is a probabilistic global search procedure that uses a local optimization algorithm solved repeatedly at several points distributed over the search domain [91]. The process implementation is simple, since the process is repeated using several random initial points; however, the disadvantages are the potential redundancy of the starting points and the escalating computational time as the number of variables increases. The Clustering optimization method is based on the Multistart method, but the algorithm intends to group the initial points to avoid redundancy. The three main steps of the algorithm are: (a) run the optimization process using random initial points across

the search domain; (b) group the sample points around common local minimum; and (c) identify points with similar characteristics which avoids solving the problem with preceding initial points in the same neighbourhood.

- *Branch and Bound*: Branch and Bound is a search method that can be applied to optimization problems when an independent variable x is restricted to a feasible region (i.e., constraint space or integer variables). The algorithm computes all the candidate solutions for the optimization problem and systematically discards non-feasible solutions by bounding the independent variables. The initial or root problem is divided into sub-problems by assigning lower and upper bounds to the independent variables, thus restricting the search domain [92]. The process continues the evaluation by dividing into succeeding sub-problems until the lower bound is equal or higher than the upper bound, at which point the algorithm has reached the resulting optimal solution.
- *Genetic Algorithms*: GAs is a heuristic approach inspired by the natural selection process in the biological world. The main difference between GA and the Multi-start or Clustering methods is that GA initiates the optimization process with an initial population as opposed to a single point. Each individual (of the population) is represented by a chromosome chain that represents a specific vector, which can be expressed as a binary or floating point representation. Each GA iteration encompasses a competitive selection among the individuals against a fitness function where the weak solutions are discarded. The vector for the solutions with the highest fitness function values are then recombined among the group using different techniques such as mutation, elitism, and crossover. The recombination process continues until a certain convergence criterion is satisfied [93]. GAs can solve non-linear discontinuous functions, since the algorithm does not require information from derivatives of the objective function.

In this thesis, an MINLP is defined and solved using GAs. The main reason for using this technique over the previously discussed ones is that GA requires information only from the objective/fitness function; hence, it is able to deal better with non-continuous constraints which are present in the LTRGP problem. Furthermore, since the planning problem for an RC microgrid is not likely to have a large number of variables, the computational time is still relatively low, as further discussed in Chapter 5.

2.5 Summary

A brief overview of microgrids and their advantages and challenges has been given in this chapter. Particularly, the current dispatch strategies for diesel-based microgrids have been presented, highlighting the characteristics of the simple, yet robust, single and parallel dispatch strategies. Furthermore, the RE equipment mathematical models, which are used in future chapters of this thesis, were discussed giving special attention to the temperature effect issue in northern locations. The advantages and current restrictions of available RE microgrids planning tools were also presented, highlighting the need for a long-term planning model for RCs considering relevant constraints. Finally, an introduction to MINLP problem was given, and some of the available solution techniques for this type of optimization problem were described, of which GA is used in this thesis, as background for the formulation of the LTRGP problem discussed in Chapter 5.

Chapter 3

Access to Electricity in Canada's Northern and Remote Communities

This chapter provides a summary and analysis of an electrical energy and natural resource survey designed to obtain relevant information about N&RCs in Canada. The chapter first presents the general methodology and challenges encountered while collecting the N&RCs energy-related information. Then, the chapter presents an estimate of the electrical generation installed capacity focusing on fuel-oil-consuming communities across the country. Furthermore, an overview of the diverse energy demand profiles, the electricity rates that apply to various types of clients and the subsidy frameworks are presented. The chapter summarizes the main challenges that the deployment of current and future electrical generation projects face. Finally, the chapter presents a summary of the detailed wind speed and solar irradiation data obtained for most N&RCs across Canada.

3.1 Database Methodology and Challenges

This section offers a description of the survey process and the types of primary sources used, as well as some of the challenges faced when acquiring information. This survey was part of a joint NRCan-funded project among Hatch Ltd., University of Waterloo, Wenvor Technologies, University of Toronto, and KLFN. The database is confidential; however, a general overview of the findings is given in this chapter with permission from the project lead (Hatch Ltd.).

3.1.1 Methodology

The survey was carried out sequentially by province and territory. The first stage of data gathering exercise for each province and territory was to find publicly available information related to N&RCs. Thus, relevant literature was reviewed to identify RC-specific keywords, and names and contacts of the individuals that could help collect related information. Hence, province-specific keywords and key-names were added to the original set of search terms, so that specific websites that were previously identified in the first stage could be searched for this expanded set of terms to gather the most relevant sources.

During the population of the database for each province and territory, there were often cases when the structure of information available did not exactly match the existing database structure. In these situations, the structures of the dataset (what information to include and how to include them) was revised accordingly, making appropriate modifications.

The main types of primary sources used for the survey were:

- *Electricity rate application documents*: These documents contain information regarding the cost of operation, and the generating and distribution assets of a utility, as well as a large variety of market information regarding N&RCs grids.
- *Request for proposals/Request for information*: In the event a utility had solicited engineering energy solutions for RCs, Request for Proposals (RFPs) or Request for Information (RFI) were available, which were a valuable source of information on the status of RCs' grids.
- *Technical presentations for energy projects*: This source of information included mainly technical presentations in symposiums and related conferences. The purpose of these documents was to present the status of RE-related projects in Canada's RCs, and contained miscellaneous system and economic information.
- *Electricity rates documents*: These documents provided the electricity rate structure for RCs, as well as the different types of customers present in each community.
- *Electrical market policy presentations*: As a public relations effort, many utilities have authored public relations documents that are introductory sources of RC-relevant information. These provided an overview that further guided the survey, as well as some numerical data.

- *Direct liaison with utilities personnel:* Utility contacts were identified using the aforementioned sources, and a dialogue was established to obtain up to date and accurate information.

3.1.2 Challenges

The survey effort was successful in obtaining energy information about N&RCs; however, there were several challenges encountered that had an adverse effect on the completeness of the survey, such as:

- *Time delays in replies to requests:* In the absence of public information, staff members of relevant institutions were contacted. Some of these contacts responded in a timely manner with useful information; however, some did not reply or replied with no intention to provide additional information. Further liaison with additional contacts occurred, but this extended the survey period.
- *Data sources from different time periods:* Due to the varied nature of the types of information available, not all information was available for the same time period. Hence, inter-community comparisons were only possible for sufficiently close time periods.
- *Lack of standardized record-keeping formats:* There was a lack of standardization of how records are kept across different provinces, companies, and institutions. As a result, a sufficiently large body of information had to be collected for each province, adjusting the structure of the database accordingly for each province and territory.

3.2 Canadian N&RCs' Grids and Microgrids

Approximately 280 N&RCs are scattered across Canada (Figure 3.1) and their population encompasses aboriginal and non-aboriginal groups [94]. Aboriginal First Nation groups are mostly in Ontario, Northwest Territories, Yukon, Manitoba, Saskatchewan, and British Columbia. These groups are governed by a Band council preceded by a chief, who can lead a single or multiple communities. Inuit communities are distributed across Labrador, Northwest Territories, and predominantly Nunavut. The Inuit have a self-governing body

with a non-profit organization, Inuit Tapiriit Kanatami, who deals directly with the government of Canada in related matters. Non-aboriginal groups are mainly in British Columbia, Newfoundland and Labrador, and the Yukon.

From an electricity perspective, these communities represent isolated microgrids and grids that range from 100 kW to 150 MW in installed capacity [29, 95–99]. Figure 3.1 shows a classification for such microgrids/grids based on their installed capacity. The relatively large urban centres have an installed capacity greater than 20 MW, typically supplied by hydro or fuel-oil sources; these large communities usually supply a large central load as well as nearby satellite communities through a distribution system usually in the 4.6 to 25 kV voltage range. There are 6 communities with installed capacities in the 5-20 MW range (orange and blue), mostly supplied by diesel fuel for electricity generation. The rest are less than 5 MW microgrids (yellow and red) with limited access. Figure 3.1 also shows communities where data was not available (green); however, based on population density, most of these communities are likely to have an installed capacity of less than 1 MW, with diesel fuel as their main source for generating electricity.

The diversity of these communities also extends to the type of utility operating the generation and distribution systems. Nearly 65% of the N&RCs are supplied by a provincial or territory-wide utility, and the remaining sites are operated by community-owned utilities (Figure 3.2). Energy information for large province-wide utilities is typically easier to acquire, since such organizations have a large database infrastructure. From an operation perspective, they also have sufficient technical and economic resources available to maintain systems running efficiently. In contrast, information from community-based utilities is difficult to acquire, and from the limited information available, they are likely to have limited operation and maintenance programs. These independent utilities are mostly in Ontario and British Columbia.

3.3 Electricity Generation

Most of N&RCs supply electricity via hydro and oil-based resources; however, the energy mix varies significantly by location. The total N&RCs installed capacity is estimated at 615 MW, with 190 MW of hydro power, 330 MW of diesel generators, 67 MW of heavy fuel oil generators, 7.7+ MW of natural gas turbines, with the remaining capacity being relatively small wind and solar systems (Figure 3.3) [29, 95–99]. In British Columbia, Manitoba, Newfoundland and Labrador, Nunavut and Ontario, diesel generators are the

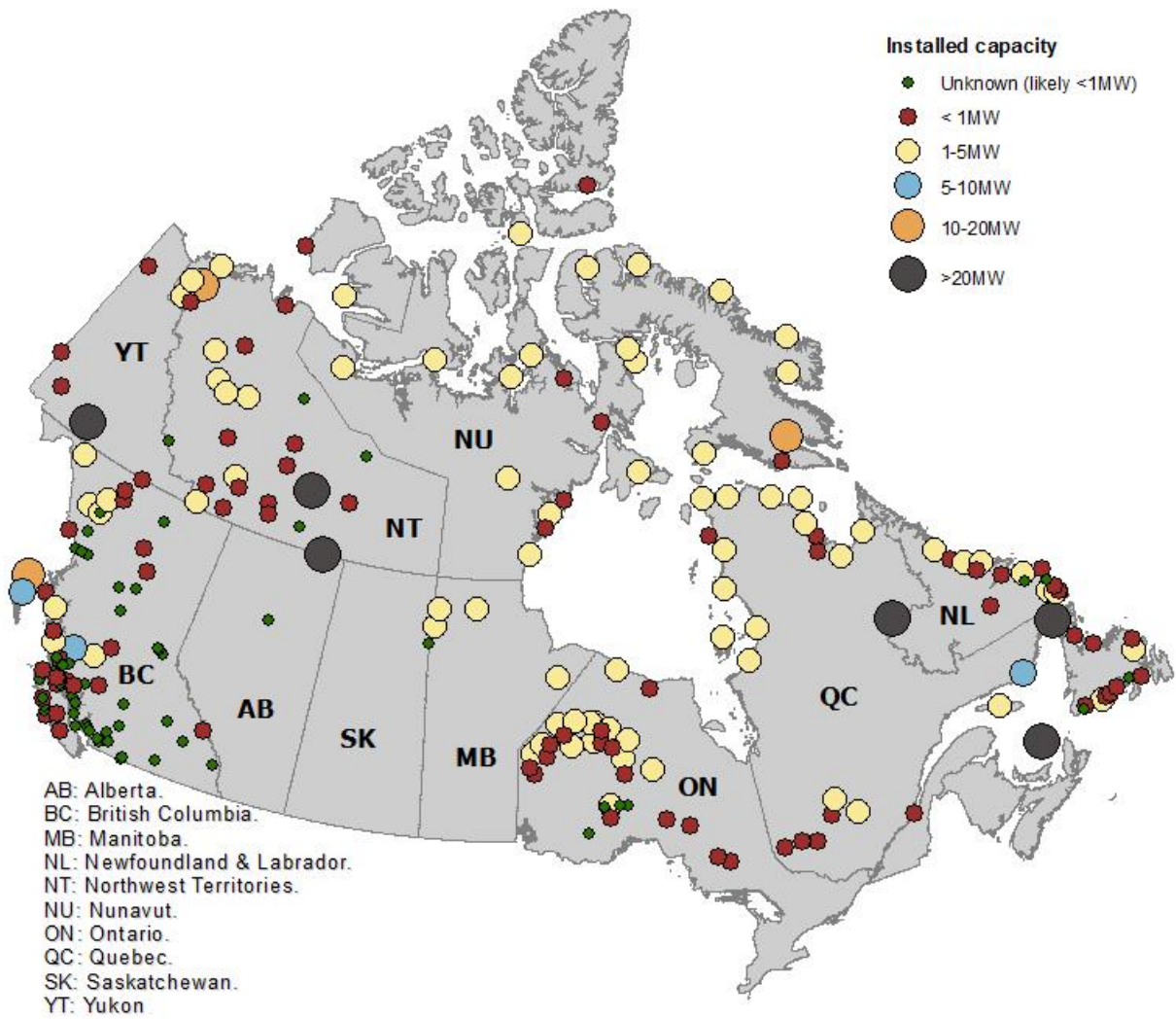


Figure 3.1: Classification of Canada's N&RCs based on electricity generation installed capacity.

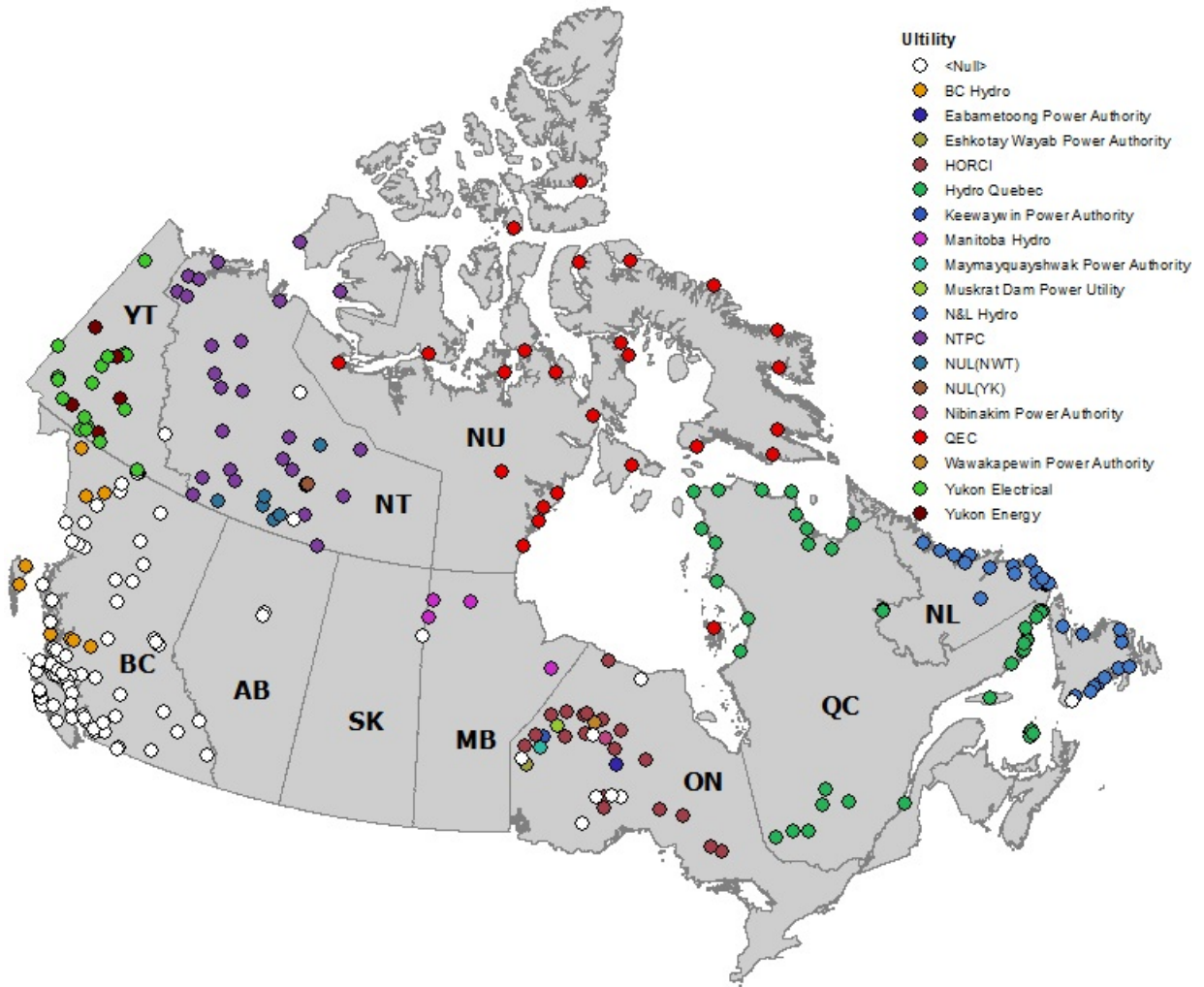


Figure 3.2: Utilities operating in Canada's N&RCs.

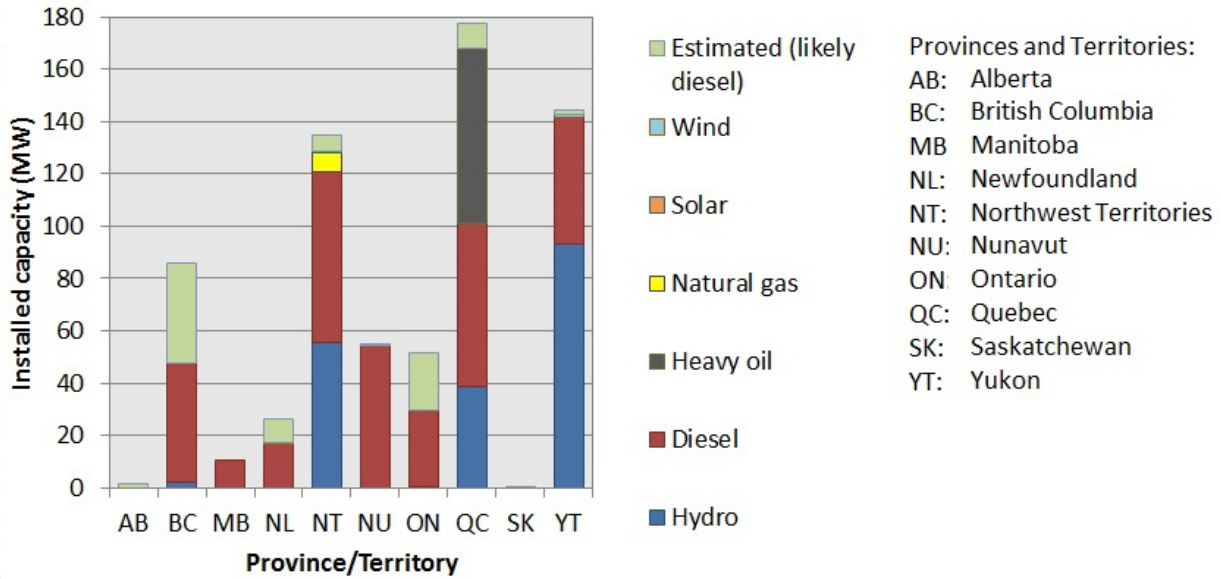


Figure 3.3: N&RCs electrical equipment installed capacity by province and energy source.

main power source for their RCs, with only a few exceptions using hydro power as a secondary electricity source. The Northwest Territories and Yukon have relatively large distribution systems with hydro-power as their primary energy source; only smaller RCs use diesel fuel as the main electricity generation source. In the Northwest Territories, there are two communities that have natural gas facilities, mainly due to the existence of on-site deposits, with no fuel transportation required. Quebec has three large grids running with different sources: the Lac Robertson and Schefferville systems run on hydro power, while the Îles-de-la-Madeleine system is the only off-grid plant in Canada running on heavy fuel oil, with a significantly higher efficiency than diesel; the rest of the communities are small and run on diesel generators.

If large hydro power facilities are excluded, RE has yet to have a significant contribution to the energy mix in N&RCs. As previously mentioned, there are relevant past and ongoing studies and projects that have been paving the path to overcome the technical, social, economic, and political barriers preventing a significant RE growth. Based on the existing diesel-based capacity, there is significant potential for RE to contribute to the development of N&RCs, if the various issues associated with RE cost, deployment, operation, and maintenance are properly addressed.

Diesel-based equipment operation is, as expected and analyzed in the next section, a

key driver of the high energy costs in N&RCs. The equipment and facilities employed in N&RCs have certainly some differences; however, the following list presents the common characteristics among the various facilities that contribute to the high energy costs:

- Approximately 90% of the diesel engines in operation in RCs have a capacity in the range 100 kW to 3 MW. Most RCs' generation facilities have a 3-5 diesel engine unit configuration. The specific sizes depend on the operation strategy of the utility. Some utilities operate the units in parallel, where the diesel generators have similar rated capacities. Others operate mainly with a single unit strategy; in this case, the diesel generators have different rated capacities ranging from the expected minimum to maximum load of the community.
- The rated plant capacities of the diesel generation facilities are typically 40%-60% of the total in-house installed capacity. All utilities always have a contingency plan to keep operating in the event of a unit failing; if required, load shedding is an alternative.
- There are several factors that affect diesel engine efficiency, such as preventive maintenance, diesel fuel quality, and engine loading. In RCs, these factors likely play a major role which creates a significant variation across facilities. The diesel fuel to electric energy conversion efficiency range is 2.4-3.9 kWh/litre, with a 3.5 kWh/litre average. In the case of the heavy fuel oil plant in the Îles-de-la-Madeleine, the fuel efficiency is 4.6 kWh/litre.
- The sources of electrical losses are difficult to determine and their variation across different utilities is significant. Based on the information provided by the utilities, the losses range from 5% to 20%.
- Fuel supply channels vary significantly across N&RCs mainly due to access restrictions, season and fuel storage capacity. Access to these N&RCs can be a combination of road (year-round and winter-only), rail, barge, and air access. Some communities are able to store a full year supply in local tanks, while others can only store for a few months of demand on-site (Figures 3.4 and 3.5).



Figure 3.4: Air-access is the only means of transportation available for some RCs during certain seasons of the year.



Figure 3.5: Fuel transportation to RCs is an expensive operation since in some locations most of the fuel is flown in (photo courtesy of Oliver Johnson).

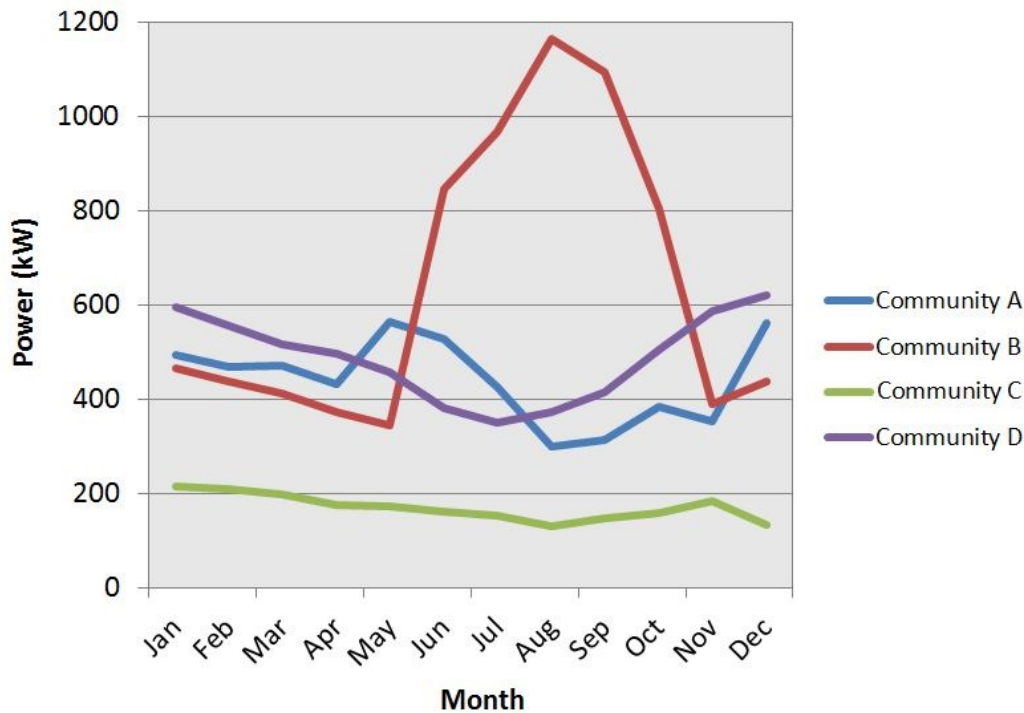


Figure 3.6: Annual load profile examples for selected RCs across Canada.

3.4 Electricity Demand and Fuel Consumption

The electricity demand and profile differ significantly from those for on-grid systems in each province. For example, in 2010, the average electricity consumption in the country was 15.1 MWh/year per capita, while the estimated range for N&RCs, where information was available, was 3.5 to 18 MWh/year per capita [100]. This wide range also applies to the electric load profile, which presents significant differences across communities (Figure 3.6); for example, community B has a significantly high seasonal load peak that is likely related to a certain economic activity, e.g., fishing. The reasons for the wide range likely include the type and quantity of electrical loads serviced, cut-off rates, daylight hours, local industry development (e.g., mining and fisheries), and seasonal services. This load variation highlights the importance of understanding the community use of electricity, and being cautious with regard to assumptions made where information might not be readily available or existent.

Diesel and heavy oil are the energy sources used to supply electricity to more than two

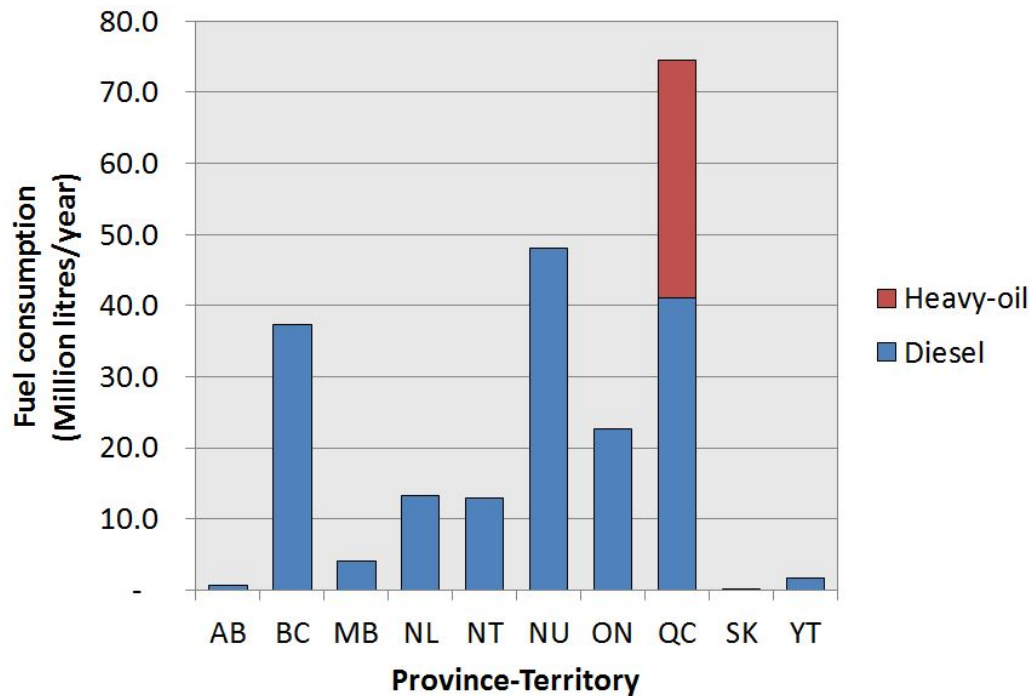


Figure 3.7: Fuel consumption for electricity generation per province and territory.

third of the N&RCs. The estimated annual fuel consumption for electricity generation in the North is 215 million litres (corresponding to approximately 600 kton CO₂eq), and its breakdown by province and territory is shown in Figure 3.7. Approximately 60% of the fuel is consumed by British Columbia, Nunavut, and Quebec; with the exception of the Îles-de-la-Madeleine and Iqaluit, all serviced communities have relatively small grids (microgrids). Evidently, the rising fuel and shipping costs have a direct impact on the energy prices in the North. The next section will examine the wide range of electricity rates based on fuel source, access, intended use, and type of customer.

3.5 Electricity Rates

The cost of supplying services to the North is high, and electricity is no exception. As with regular electricity rates, the price depends on the energy sources available, but in the case of N&RCs, access, utility type, and customer classification play a significant role in determining the corresponding electricity rate (e.g., [101–103]). Regardless, the costs

are primarily covered by government, under different provincial and/or federal agencies and payment frameworks. The government agencies' roles and detailed structures are beyond this chapter's scope, since it is an extensive topic; however, a general perspective for rates can be formulated without getting into further details regarding the role of each stakeholder. The rates structure varies by province and territory, and it is challenging to make a direct comparison among them; however, a simplified classification is given next to provide a general economic perspective of electricity rates in N&RCs.

The electricity rates vary among customers and are set to cover the operation costs, and reflect the subsidy framework available for each rate. Figure 3.8 presents a simplified classification of the diverse electricity rates by customer type, government involvement, and end-use of electricity (residential and general services). Figure 3.8(a) shows the non-government residential rates which are generally lower than the total operation costs, especially for diesel-based locations. In the case of provinces, these lower rates are set to match the equivalent on-grid electricity rates; for the territories, the rates are set to match the tariffs charged in their respective capitals (Yellowknife, Whitehorse and Iqaluit). Figure 3.8(b) shows the non-government general service rate, which in most locations is similar to the residential tariff; the differences depend on the subsidy levels of commercial clients. For the previous rates, an energy cut-off scheme applies in which a tariff closer to the operation cost is charged after certain consumption level is reached (e.g., in NT, the base rate for Sachs Harbour is \$0.26/kWh and in the winter, after 1,000 kWh/month, the rate increases to \$0.54/kWh). An important objective of this scheme is to discourage the use of electricity for heating purposes. Figures 3.8(c) and (d) present the government rates for residential and general services uses, respectively. These rates are commonly higher than the non-government rates and nearly reflect the average operation costs in the region. How the rates are set in each location depends on the utility; some utilities calculate an average operation cost based on a specific region, while others set a distinct tariff by community.

A subsidy framework is required to bridge the gap between the operation costs and the lower non-government rates. These frameworks can involve federal and/or provincial agencies, and vary significantly by province and territory, type of utility, customer type, and diesel-fuel price. For example, British Columbia has a high subsidy for the delivered diesel fuel price, which leads to low electricity rates for all customers. In Ontario, the diesel fuel prices are the same as those in the rest of the province, which after adding transportation costs, makes operation and maintenance costs approximately 8-10 times that the on-grid residential rate. The government of Ontario has a provincial fund in place to support utility-operated communities, while AANDC supports community-operated lo-

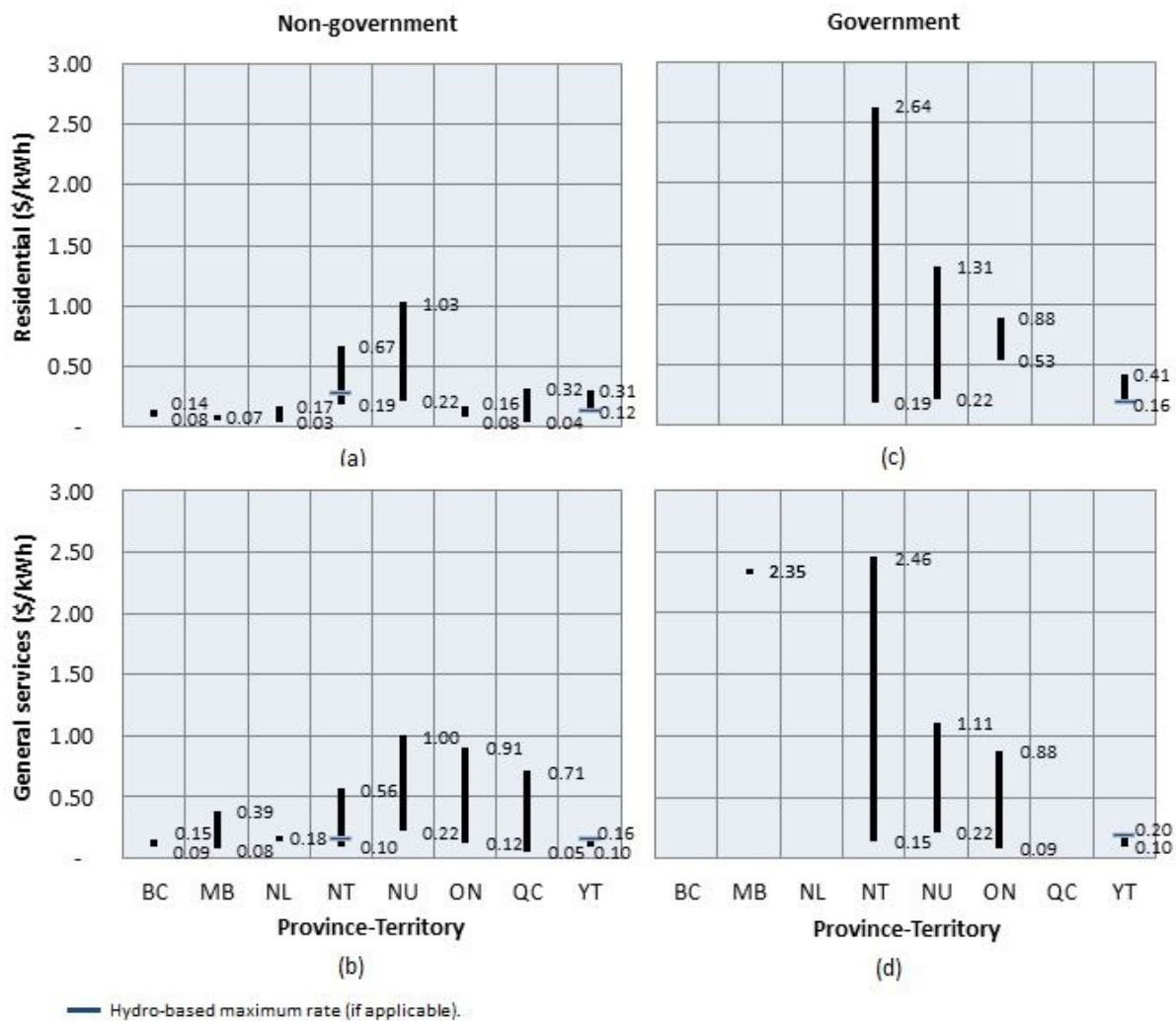


Figure 3.8: N&RCs' electricity rates by province and territory for (a) non-government residential, (b) non-government general services, (c) government residential, and (d) government general services.

cations. In Manitoba, the governmental rate is calculated to pay for the gap between the total generation costs and the non-government rates; thus, the high discrepancy between the subsidized and un-subsidized prices.

3.6 Energy-related Issues

From the previous discussions, it is clear that there are significant energy challenges that N&RCs currently face. The following list summarizes the main issues:

- *Fossil fuel dependency*: The estimated fuel consumption (215 million litres/year) only accounts for the diesel and heavy oil required to generate electricity in communities where the primary energy source is fuel-based. This consumption has an environmental footprint of approximately 4.8 tCO₂eq per capita for diesel-based communities, while the Canadian emission average for electricity generation was 2.6 tCO₂eq per capita in 2011. The fuel dependency and related environmental impacts are even greater if one considers the diesel required for fuel transportation and heating requirements.
- *Load restrictions*: Peak demands in some RCs have reached or are close to reaching rated plant capacities [104]. This leads to communities with load restrictions, which means that no more buildings can be built and/or connected to the local grid until additional generation equipment is installed or other similar buildings are permanently disconnected from the system.
- *Deployment costs*: Limited access for fuel transportation is one of the main drivers for high energy costs, and the same applies to equipment deployment, operation and maintenance in N&RCs, which limit the economic viability of potential projects. Installation and maintenance costs of previous and current energy projects in N&RCs are not widely documented, but based on the information provided by reliable sources, project costs can easily double those of an equivalent on-grid project.
- *Operation and avoided fuel costs*: The high energy costs in a diesel-based community could make an RE project economically feasible. However, from a utility perspective, the potential savings are not defined by the total energy cost, since indirect costs are not likely to decrease; hence, only fuel-related or avoided fuel costs should be considered in this case. Depending on the community, the utility should be able to determine a calculated avoided fuel cost which could range from 50% to 60% of the total energy cost.
- *Subsidy frameworks*: Electricity rates and subsidy frameworks are relatively complex mechanisms that need to be properly considered to assess if the stakeholders would

benefit from potential energy-related projects. Without any changes to the existing subsidy framework or without proper incentives, it is difficult to conceive RE-based projects that would interest the community.

- *Unbalanced loads*: In some communities during light-load conditions, three-phase distribution system can reach unbalances of 10% or higher. This situation could lead to potential premature failures in the generators due to undesirable mechanical vibrations. If this situation is encountered frequently, utilities may re-distribute the load across the three phases depending on the season, which is an expensive practice.
- *Winter roads*: Winter season weather variations have a significant effect on the conditions of ice-roads and their serviceable lifetime, resulting in variable weight restrictions for such roads depending on the weather conditions. For example, in northern Ontario in 2012, the weight limit for vehicles using ice-roads was dropped from 80,000 to 40,000 pounds due to reduced ice-thickness; as a result, fuel trucks had to be sent to RCs with partial loads. In addition, winter-roads are maintained by different parties, and thus proper coordination is required to ensure that vehicles can reach the intended destinations.
- *Community-operated utilities*: Obtaining energy-related information for community-operated utilities can be a significant challenge. These utilities can also have different operating standards than their provincial and/or territorial counterparts. As a result, community-operated utilities may deal with different issues on top of those previously mentioned.

3.7 Wind and Solar Resources in N&RCs

This section presents Canada-wide maps displaying the collected wind and solar resource data in N&RCs. The data presented is a summary of the annual average solar irradiation and wind speed obtained for each location; nevertheless, as part of this research, 1-hr time series data has also been collected for most sites for both resources. The intention of this detailed data is to be used as an input to the LTRGP presented in the next chapters.

3.7.1 Solar Irradiation Data

Solar irradiation information is widely available in the literature with different levels of resolution [105, 106]. However, detailed solar irradiation information is to a certain degree available only for sites below latitude 58°N . In Canada, this is a challenge for northern locations, since approximately 100 communities and 100,000 people (covering one third of the total N&RCs) are located at higher latitudes. Additionally, some of the typical available information extends to both Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI); GHI is useful for sites where fixed solar arrays are intended, while DNI is useful for sites where solar tracking systems are to be considered.

Based on the survey of Canada's RE projects presented in Chapter 1, fixed solar arrays are preferred; one of the main reasons is the O&M issues related to high temperature ranges and PV panels tracking systems. Figure 3.9 presents the map for the annual GHI averages obtained from National Aeronautical and Space Administration (NASA) for all N&RCs. In addition, solar irradiation information is available from NRCan at a higher level of resolution (1-hour); yet, this information is only available until 2008 and for locations south of 58°N .

3.7.2 Wind Speed Data

Low-resolution wind speed data can be readily obtained from different sources; however, this data is usually limited to seasonal or annual averages [107]. On-site wind speed data is seldom available for RCs; thus, meteorological models data is the next alternative data source [108]. Such information was obtained for this research at 1-hour time resolution at different hub heights (20, 50 and 80 meters), together with the respective Weibull distribution scale and shape parameters. This study provides a comprehensive data set for annual wind speed distribution that is also used as an input for the LTRGP models described in the next chapters. Figure 3.10 illustrates the annual average wind speed ranges for most of the N&RCs at a 50-meter height.

3.8 Summary

A general overview of different technical, economic, social, policy, and environmental issues that need to be considered to properly understand the electric energy situation in N&RCs

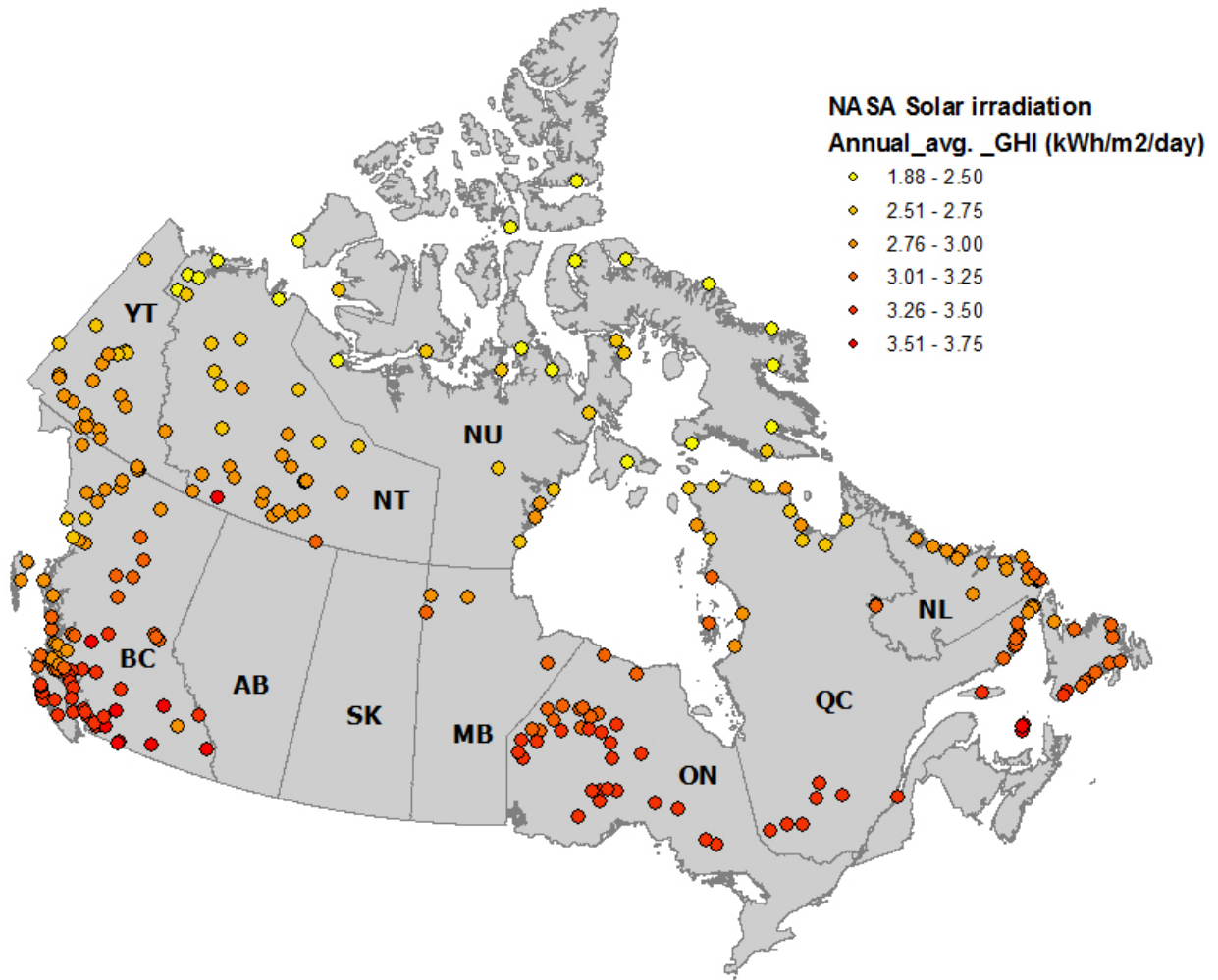


Figure 3.9: GHI information for N&RCs.

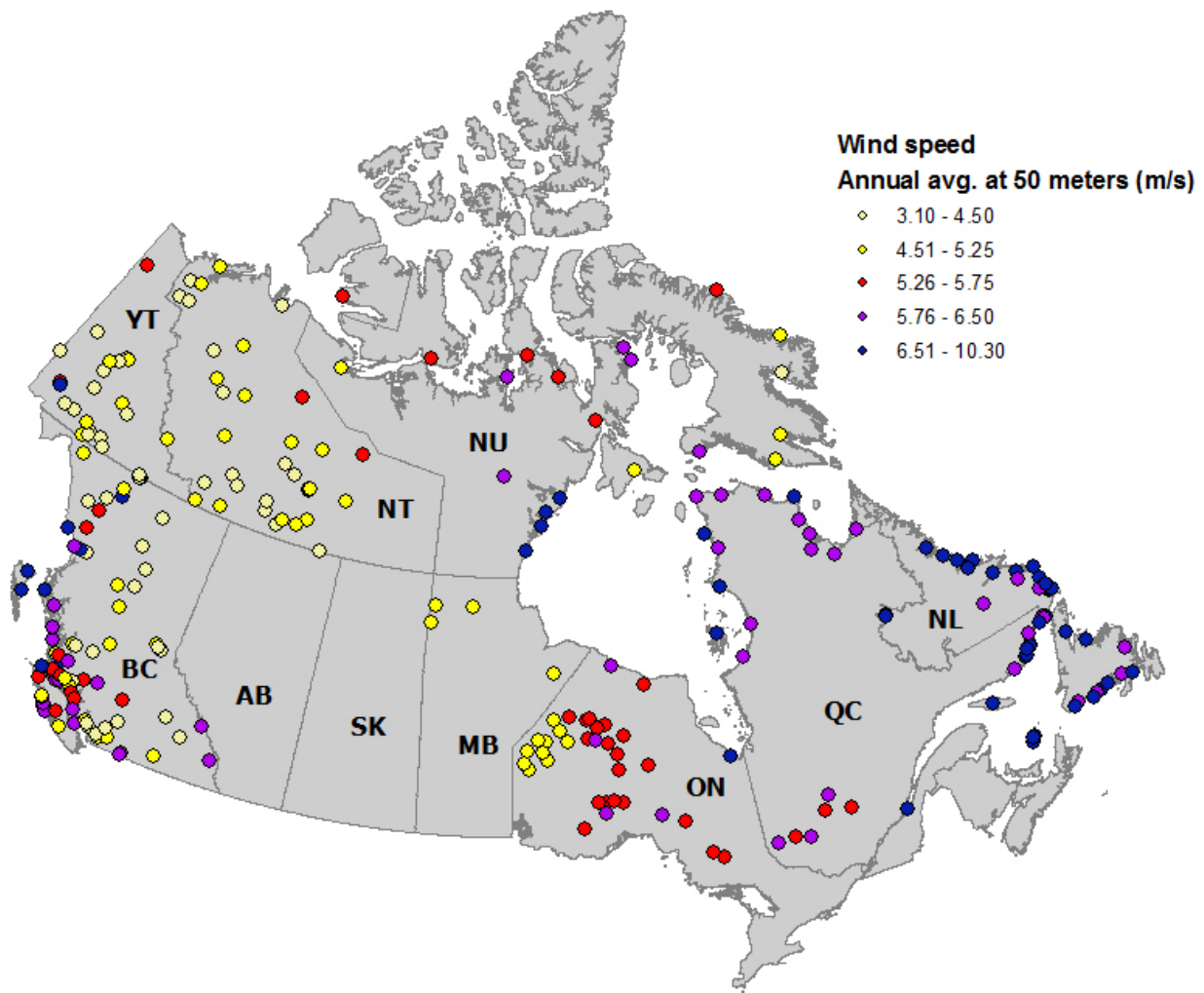


Figure 3.10: Annual average wind speed at N&RCs.

has been presented in this chapter. A summary of the solar and wind resources obtained as part of this research was also presented, including some of the related maps produced in the course of study, and discussing the benefits and limitations of using the available time-series data to propose RE projects in Canada's remote locations.

The main objective of this chapter is to provide a better understanding of the challenges and opportunities with regard to electricity generation in Canada's N&RCs. There is significant RE potential in N&RCs; however, more than half of the people in these communities still rely solely on fuel-based sources for electricity generation, mainly due to the

communities' geographical locations and low population densities. Recent RE studies and projects have aimed at slowly changing the perception that diesel fuel is the sole alternative for such communities; however, there are still significant challenges involved in changing the existing energy mix to include significant contributions from RE sources.

The content of this chapter has been published in [\[94\]](#).

Chapter 4

Microgrid RE Generation Planning Based on Existing Tools

This chapter investigates RE alternatives that can potentially reduce diesel fuel dependency of electricity generation in Ontario’s remote northern communities. The chapter presents the challenges for RE projects in northern Ontario, analyzing the current economic structure, high capital costs, available natural resources, equipment deployment, and O&M complexity. It also discusses the RE planning problem for RCs based on a currently available planning tool. Finally, an RE planning case study based on the KLFN community is presented. This case study presents low and medium RE penetration scenarios for the community, and the technical, economic, and environmental outcomes.

4.1 Energy Status of Northern Ontario Remote Communities

Ontario has more than 31 RCs where off-grid diesel-based microgrids supply electricity to the population; 21 of these communities are operated by the provincial utility, Hydro One, and 10+ communities are operated by community-based utilities, as briefly mentioned in Chapter 3. Table 4.1 shows a summary of the energy status of the communities where electricity generation, fuel consumption, and CO₂ emission data were available at the time of this study.

Table 4.1: Electric energy supply status for Ontario's RCs.

Community	Population	Fuel consumption (lt/year $\times 10^6$)	Energy supply (GWh/ year)	CO ₂ emissions (kton)	Annual average loading levels ¹ (2010)
Hydro One Operated Communities					
Bearskin Lake	499	0.76	2.73	2.2	50-60%
Deer Lake Lake	800	0.8	3.8	2.3	N/A
Fort Severn	449	0.79	2.65	2.3	75%
Gull Bay	452	0.32	1.09	0.9	70-75%
Kasabonika Lake	862	1.01	3.63	2.9	90%
Kingfisher Lake	313	0.58	1.90	1.7	82%
Kitchenuhm...	883	1.51	5.55	4.3	78%
Landsdowne H.	300	0.62	2.06	1.8	N/A
N.Caribou Lake	702	1.17	4.22	3.3	77%
Sachigo Lake	460	0.82	2.86	2.4	65%
Sandy Lake	2,111	2.95	10.77	8.5	70%
Wapekeka	341	0.68	2.13	1.9	75%
Webequie	622	0.77	2.74	2.2	75% ²
Others	800	1.22	4.20	3.3	-
Subtotal	9,594	14.01	50.33	40	
Community-based Operated Communities					
Eabametoong	1,140	1.73	6.17	4.98	-
Kee-Way-Win	320	0.66	2.36	1.91	-
Muskrat Dam L.	255	0.39	1.38	1.11	-
Neskantaga F.N.	265	0.53	1.9	1.53	-
North Spirit L.	255	0.49	1.74	1.41	-
Peawanuck	139	0.34	1.23	0.99	-
Pikangikum	2,443	3.71	13.22	10.66	-
Wawakapewin	47	0.06	0.22	0.18	-
Weenusk	225	0.34	1.22	0.98	-
Wunnumin	490	0.59	2.09	1.69	-
Subtotal	5,579	8.86	31.54	25.43	
Total	15,173	22.87	81.87	65.43	

¹Percentage of the maximum annual load demand over the diesel plant rated capacity.

²On-going projects to increase installed capacity.

In 2008, the communities' electricity demand per capita (5,395 kWh/year/person) was 70% lower than Canada's national average (17,061 kWh/year/person); similarly, CO₂ emissions were 73% lower than the national average [109]. The lower electricity demand is in part a consequence of the cap set by the limited installed capacity, as discussed in Chapter 3. Currently, some of these communities are about to reach their diesel plant rated capacity, due to the increasing demand and lack of capital funds for expansions. If the peak demand reaches 75% of the generation capacity, the community falls into a Load Restriction (LRes) status; as the name suggests, this requires the community to hold off any building construction or economic growth projects that would increase the electrical load. The load levels with reference to installed capacity were solely available for Hydro One-operated communities, where six communities have already reached the 75% limit and are thus in LRes. Nearly half of these communities are already considering new alternatives or expansion projects to maintain a reliable source of electricity without drastic restrictions; some of them are mostly considering diesel generators to increase their electricity generation capacity. Hence, it is important to examine RE alternatives that can partially overcome the current electrical restrictions, while reducing carbon emissions and O&M costs.

4.1.1 Electricity Model Structure and Costs

4.1.1.1 Electricity Generation Stakeholders

The electricity cost model for the RCs in Ontario involves four stakeholders: the provincial government, the utility, the local fuel supplier, and the customers. The Government of Ontario, through the Ontario Energy Board, sets regulations for supplying service to these communities, which includes the baseline for the electrical subsidy under the Rural or Remote Electricity Rate Protection (RRRP); province wide, utilities charge 0.13 cts/kWh as the RRRP subsidy [110].

HORCI is a non-for-profit Crown Corporation that has the government mandate of supplying electricity to RCs, and it is responsible for the O&M of the diesel generators. In some communities, HORCI purchases diesel-fuel directly from the community, which represents an income for the community. Customers that do not receive direct or indirect funding at these communities pay a subsidized electricity price approximately equal to what Ontario's on-grid customers pay [111]. Figure 4.1 summarizes the stakeholders' participation in the electricity generation activities, showing that capital projects are typi-

cally the responsibility of the community, with the required funds coming from the federal government.

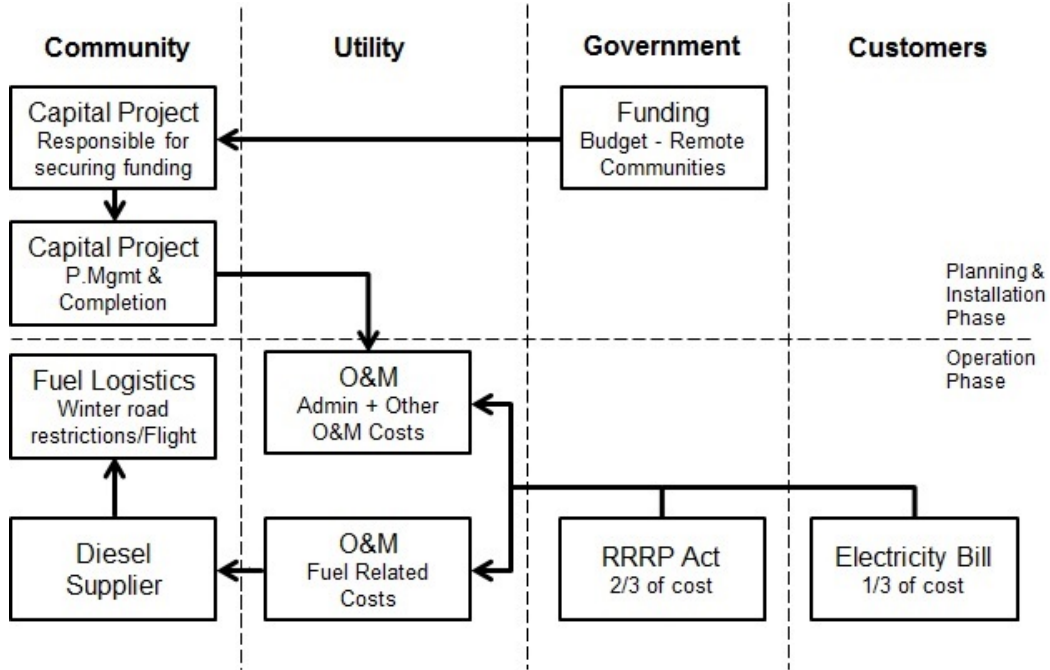


Figure 4.1: Stakeholders' cash flow from electric generation activities.

The O&M, from the utility point of view, is a zero-sum process. In 2008, HORCI estimated an annual expense of \$45.2M, of which \$15.1M was recovered through customers, and the remaining \$30.1M was paid from the RRRP budget [111]. In the current business model, the utility and the community have low or non-existent incentives to reduce operating expenses.

4.1.1.2 Current Operation and Maintenance Costs

For HORCI-operated communities, the electricity cost can be estimated using Table 4.1 and the utility's annual budget forecast. The total electricity demand for all HORCI operated communities is estimated at 57 GWh/year, which is 15% larger than the 2004 values. Since HORCI's 2008 annual expense was \$45M, an estimated O&M average electricity cost of \$0.80/kWh can be calculated from this annual energy output y the total operation expense; however, the community's remoteness influences the electricity cost significantly.

The O&M cost can be estimated using the total fuel consumption, HORCI's expenses, current fuel prices, and assuming a linear relationship between latitude and diesel-fuel price. For example, Gull Bay is 183 km from Thunder Bay with all-year road access; hence, considering the current diesel retail pump price at Thunder Bay, the O&M electricity costs can be estimated to be \$0.4/kWh. In contrast, Fort Severn is 850 km north of Thunder Bay with limited accessibility due to its remote location, resulting in an estimated O&M electricity cost of \$1.2/kWh.

In Ontario, diesel fuel prices continue to rise steadily, directly increasing the electricity cost for northern communities. In 2011, the annual average cost of diesel fuel for Northern Ontario was \$1.24/litre, i.e., 24% higher than the 2010 average and 74% higher than that in 2001. With the current fuel price trend, the average cost of electricity in these RCs could increase to \$1.12/kWh (40% increase) in the next 10 years. Hence, for example, Gull Bay's and Fort Severn's electricity costs could conservatively rise to \$0.56/kWh and \$1.68/kWh, respectively, in a 10-year period.

4.1.2 Carbon Emissions and Environmental Issues

CO₂ emissions are an inherent disadvantage of supplying electricity using diesel generators. The electrical generation in the 21 HORCI-operated communities accounts for 40,000 tons of CO₂ equivalent emission annually [112]. This value is equivalent to the annual emissions of approximately 8,400 passenger vehicles [113]. Fuel transportation and storage is also considered an environmental hazard. Potential leaks and spills during transportation and storage could be reduced if less fuel is required for electricity generation when RE technologies are added to the electricity generation mix.

4.1.3 RE-based Microgrid Operating Issues

Installation of RE equipment in northern remote locations has inherent technical operation challenges that are related to equipment and/or RE-penetration levels. Equipment performance and reliability depend on various issues, such as low-load conditions, lower efficiency, and premature wear for diesel generators. FGs in northern remote locations are usually oversized due to the large difference between average and peak loads, and as a result, generators usually run at partial load resulting in lower efficiency rates; most northern RCs have generators with different rated capacities to partially overcome low-load issues [20].

Furthermore, the generator’s efficiency is likely to be further reduced when RE equipment is integrated into the microgrid, due to the negative load that RE generation implies. RE integration would likely keep diesel generators running longer at partial load conditions, which will result in carbon build up in cylinder heads and pistons, that can be potentially overcome by succeeding periods of full-load runtime [114, 115]. In addition, integration of an intermittent RE source would result in heavy, pulsating loads that can potentially cause surface fatigue and eventually cracks in the engine bearings [114].

As RE penetration levels increase, the requirement for more advanced equipment also increases to ensure stable operation of RE-diesel-microgrids. An EMS would be required to efficiently control the different energy sources [116]. Also, quick diesel engine governors are required to compensate for wind fluctuations to avoid adverse impact on grid frequency [117]. Synchronous condenser(s) might be required to maintain voltage stability in the system; this could be accomplished using one of the existing generators at no load, given that can be decoupled from the diesel engine [118]. There is also the need for dump loads to handle excess RE, and thus avoid frequency stability problems [118]. Finally, at high RE penetration levels, diesel plants could potentially be turned off for some time periods; hence, in cold climates, a diesel plant heating system is needed to assure that the engines can start-up again quickly [118].

4.2 Mathematical Model

On-site wind and solar information is scarce in RCs; hence, these resources are estimated here using existing mesoscale resources. For this study, 22 RCs were identified in the province of Ontario; 13 operated by HORCI and 9 operated by community-owned utilities. In addition, the mathematical generation model used in this work for the different system scenarios are those available in the distributed generation package used, i.e. HOMER [32], where only a simple power balance equation is assumed, with no representation of the grid. A detailed description of these models can be found in [32, 119]. The model inputs are the community load demand, the estimated energy resources, and the RE equipment described in this work. The software then considers different dispatch strategy that will yield the minimum project cost for each equipment configuration. Finally, the optimal solution for each scenario is found by computing the Internal Rate of Return (IRR) for all configurations in the search space, and selecting the configuration with the highest IRR. The next sections describe in detail the modeling of the wind and solar resources, and

the dispatch strategies of diesel generators and batteries that are directly relevant to the remote microgrids considered in this thesis.

4.2.1 Wind and Solar Resources

On-site, 10-min average data for at least a year is required to properly assess the wind profile in any given location and determine the optimal on-site location for WTs [72]. However, the author of this thesis is not aware of available raw wind data for any of the considered RCs. Since, the installation of proper measuring equipment at different heights is desirable, this should be considered as an essential part of any future northern wind project deployment, detailed wind data is of special interest for small wind projects, as the local terrain can considerably change the wind regime [75]. Given the fact that no detailed data is available, average wind speed information obtained from the Canadian National Wind Atlas is used here [107].

On-site solar data is similarly not available for the communities considered; however, a solar irradiation estimate can be obtained from [105]. Due to similar latitudes of the sites, the solar resource is fairly constant across the province, with solar irradiation in the communities varying from 3.12 to 3.49 kWh/m²/day. Hence, a solar project in one community could be considered a reference to be replicated in other communities with comparable energy output. Yet, on-site solar measurement equipment should be considered as part of a deployment project to reduce solar resource uncertainty.

The wind resource varies considerably based on the location, while the solar resource stays fairly constant for the studied northern communities. An objective high-level comparison of the suitable approaches for individual communities can be performed by comparing CFs for both technologies at each site. The wind CF calculation depends on the selected WT; the power curve of an Endurance E-3120 50 kW wind turbine is used here due to its low cut-in speed of 3.5 m/s, and rated power at 9.5 m/s [120]. The wind CF formula used in this study is:

$$CF_{WT} = \sum_{j=1}^{ws_{cut-off}} \left(WD(ws_j, A_{WD}, k_{WD}) - (ws_{j-1}, A_{WD}, k_{WD}) \right) PC_k(ws_j) \frac{(1 - DF)}{HRP_k} \quad (4.1)$$

where WD is the Weibull distribution value at a specific wind speed (ws_j); A_{WD} and k_{WD} are the scale and shape factors, respectively, for the location; PC is the WT power curve

value at ws_j ; DF is the de-rating factor ($DF=10\%$); RP_k is the nominal WT rated power for equipment k ($RP_k=50$ kW); and $ws_{cut-off}$ is the WT cut-off speed. On the other hand, the solar CF is calculated considering the monthly irradiation at each site as follows:

$$CF_{PV_i} = \frac{\sum_{n=1}^{12} G_{t_n} PR}{8760} \quad (4.2)$$

where G_l represents the monthly solar irradiation in kWh/m²/day for community l , and PR is the performance ratio for the solar PV array (0.85) [121].

Figure 4.2 shows that the wind CF is higher for all analyzed communities due to the previously mentioned characteristics of the wind turbine (low cut-in speed and rated power at a low wind speed). Hence, even for communities with annual average wind speeds of as low as 4.5 m/s, the wind resource will have a higher energy output than solar. However, as it is further discussed in the next section, solar technologies in remote northern locations should still be considered an alternative due to their installation simplicity, and lower capital and O&M costs, which are important issues to consider during the decision making process.

4.2.2 Diesel and Battery Dispatch Strategy

The current dispatch strategy for the considered microgrids with multiple diesel generators is simple, reliable, and robust since only one diesel generator is operating at a time, with the exception of a few minutes of overlap. For example, the engine switching strategy for a three-diesel engine microgrid can be defined as:

$$UC_{gen}(t) = \begin{cases} [1 \ 0 \ 0] & \text{if } (\alpha_{LL}RP_{j_1} < P_D(t) < \alpha_{UL}RP_{j_1}) \ \& \ UC_{gen_2}(t - \Delta t) = 1 \\ [0 \ 1 \ 0] & \text{if } (\alpha_{LL}RP_{j_2} < P_D(t) < \alpha_{UL}RP_{j_2}) \ \& \ UC_{gen_3}(t - \Delta t) = 1 \\ [0 \ 1 \ 0] & \text{if } (\beta_{LL}RP_{j_2} < P_D(t) < \beta_{UL}RP_{j_2}) \ \& \ UC_{gen_1}(t - \Delta t) = 1 \\ [0 \ 0 \ 1] & \text{if } (\beta_{LL}RP_{j_3} < P_D(t) < \beta_{UL}RP_{j_3}) \ \& \ UC_{gen_2}(t - \Delta t) = 1 \end{cases} \quad (4.3)$$

where $UC_{gen}(t)$ is the unit commitment binary variable for the diesel generator j at time t ; $P_d(t)$ is the load demand at time t ; RP_j is the rated power for the diesel generator j , with $RP_{j_1} < RP_{j_2} < RP_{j_3}$; α_{LL} and α_{UL} are the reduced partial-load ratios' lower and upper limits, respectively; and β_{LL} and β_{UL} are the increased partial-load ratios' lower and upper

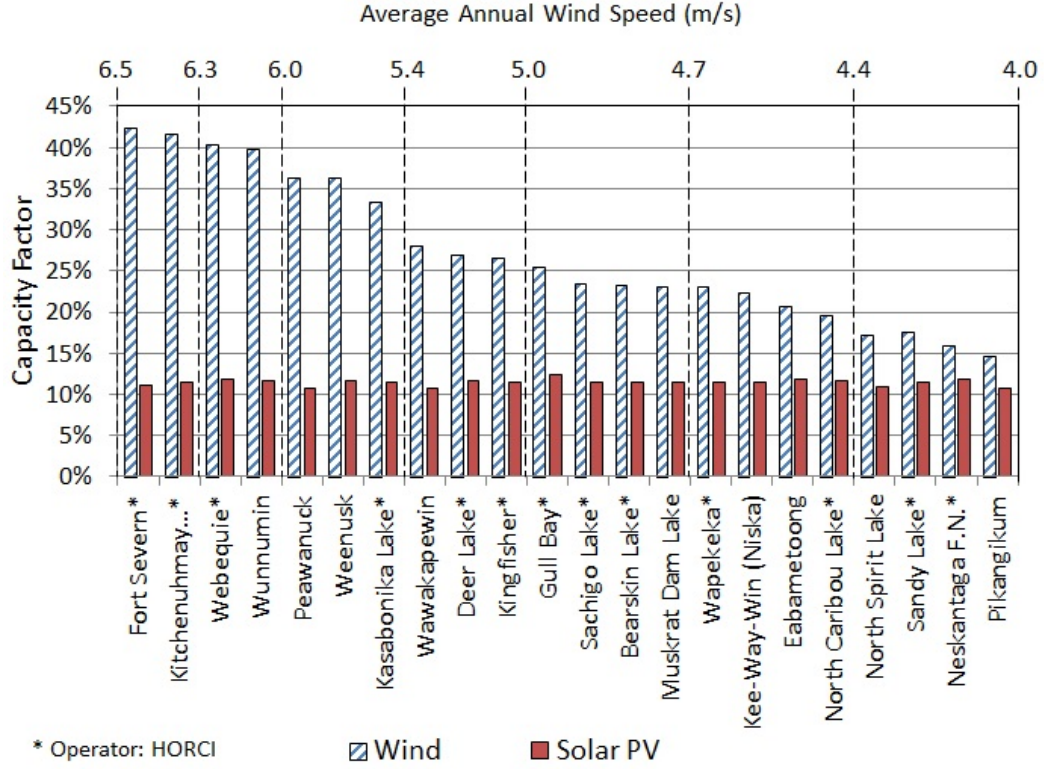


Figure 4.2: Wind and solar capacity factors for Ontario's RCs.

limits, respectively. If a low RE penetration scheme is implemented, the dispatch strategy will not probably be affected, since the RE contribution will only be seen by the system as a negative load.

As the RE-penetration level increases, the requirement for energy storage can be seen as a feasible alternative that needs to be managed simultaneously with the diesel engines. The critical load cl for cycle charging corresponds to the load value at which the cost of energy generation with the diesel engine is equal to the cost of supplying the load with the battery bank, and can be defined as [119]:

$$CL = \frac{d_{GSb_j} C_{FUEL}}{C_{BW} + C_{FUEL} d_{GSb_j} \left(\frac{1}{\eta_{RT}} - 1 \right)} \quad (4.4)$$

where d_{GSb_j} is the diesel engine fuel consumption at no load; C_{FUEL} is the diesel fuel cost; C_{BW} is the cost of battery wear; d_{GSa_j} is the incremental fuel consumption rate; and η_{RT} is

the round-trip storage efficiency. If $P_D < CL$, the RE and/or diesel generators will supply the load and charge the battery bank.

4.3 RE Alternatives for KLFN

4.3.1 The Community

KLFN, with a population of 914 people, is an RC located at 53° 31' 59"N and 88° 36' 21"W, approximately 500 km north of Thunder Bay. The community can be accessed all-year-round by plane or via winter roads, subjected to weight restrictions depending on ice-thickness conditions, which in recent years have frequently resulted in reduced load limit of 18 ton from the original 36 ton. In 2006, the total KLFN energy requirement was 13.7 GWh/year: 26% electricity, 36% wood, 18% heating fuel oil, 2% diesel (transportation), and 18% gasoline [11]. An estimated 66% of the total energy is used for space and water heating.

From the electricity perspective, KLFN currently has three installed diesel generator units, rated at 400 kW, 600 kW, and 1MW to supply the electric loads of the community. Based on the information provided by HORCI, the total daily average electricity demand was 12 MWh, with a power peak of 850 kW in 2007. Currently, the community and utility have plans to increase capacity by installing a 1.6 MW generator likely over the next year. The diesel generator plant consumes an estimated 1.2 million litres/year, equivalent to 3,600 ton equivalent CO₂/year.

Based on the information provided by the community, diesel-fuel price is \$1.8/litre, and the O&M cost is estimated at \$3.7M/year (\$1.9M fuel, \$1M direct O&M, and \$0.7M indirect/administration costs). Therefore, considering an annual electric demand of 4.4GWh, the annual O&M cost can be estimated to be \$0.84/kWh.

Besides the high electricity cost, KLFN has further electricity-related issues that affect its economic and social development. Thus, KLFN has reached 90% of its electrical capacity and it is currently under LRes. Hence, energy supply alternatives to partially alleviate the current LRes situation are a priority for KLFN.

4.3.2 RE Equipment Characteristics and Costs

Off-grid RE projects are more sensitive to cost variations than on-grid projects, due to the unique nature of most projects, which results in less standardize design processes and special deployment conditions. The cost analysis, presented next, for the installation of RE equipment (wind, solar, and battery bank) at KLFN results in a 2-2.5 times price increase compared to a similar on-grid installation. Here, the installation costs are divided into equipment, installation, project management, crane operation (if applicable) and contingency.

The wind energy conversion system used for this study is the Endurance E-3120 50 kW considered in the previous section. The WT installation cost per kW varies significantly with the rated power. As a reference, the IEA reports an average installed cost of \$1,960/kW for 2 MW WTs in Canada [122]; however, for the 50 kW small wind turbine considered, the cost for the turbine itself is approximately \$7,289/kW [76]. The WT installation and project management costs are estimated considering the IEA cost breakdown presented in [122], where 76% is the WT cost, 18% installation cost, and 6% project management cost. Hence, if WT projects were located in an easily accessible site, the total installation cost would be approximately \$9,600/kW. However, due to the site remoteness, additional costs need to be considered such as remote equipment transportation, remote crane operation, site available spare parts, and contingency. The remote transportation cost estimate, from Dryden to KLFN, based on an equipment quote provided by KLFN, is approximately \$4.65/kg (\$639/kW). The remote crane operation, based on a quote from a company based in Dryden, ON, considering \$1,600/day and 10 days for the installation process is \$640/kW. Spare parts are considered to be 10% of the equipment and installation cost (\$900/kW). Finally, the contingency cost is estimated to be 15% (\$1,632/kW), due to the uncertainty level of the operation. Hence, the total turnkey cost estimate for a WT installation at KLFN would be \$13,414/kW.

PV panels have a lower installation cost per kW when compared to small wind turbines. As a reference, the estimated equipment cost is \$3,700/kW, which accounts for the panels, converter, and connection equipment [123], and considers the current trend of price decrease of PV panels [124]. The installation cost is calculated using the KLFN service rates set at \$50/hr for certified electrician and \$37.5/hr for electrician in-training (\$1,840/kW). The estimated project management cost was estimated to be equal to that for WT installation (\$600/kW). Remote transportation costs are estimated at \$3.50/kg, which is 75% of the WT rate due to the PV panels modularity (\$653/kW). Spare parts

(\$554/kW) and contingency (1,019/kW) are estimated similarly as in the case of the WT component. As a result, the obtained turnkey cost estimate for a PV installation at KLFN would be \$8,365/kW.

The battery bank used in this study is composed of Rolls/Surrette (4KSS21P), 4 V, 1,104 Ah (4.42 kWh) [125]. The battery equipment cost is estimated from a RE seller at \$157/kWh for the battery, and \$190/kWh for the bi-directional inverter, building requirements, and connections. The installation cost is estimated using the same KLFN service rates for two people and a rental truck (\$48/kWh). The project management costs are assumed to be already included in the PV or WT installation cost, and hence not considered here. The transportation costs are calculated at \$3.5/kg, the same as that for PV installation (\$134/kWh). Costs of spare parts (\$40/kWh) and contingency (80/kWh) are estimated in a similar way to that for the WT installation. As a result, the expected turnkey cost estimate for a battery installation at KLFN would be \$650/kWh.

Table 4.2 summarizes the costs of the wind, solar, and battery bank systems. The table can be used as a reference for this and future similar remote sites. As previously mentioned, the cost is site-dependent; hence, a factor has to be added to account for the transportation and installation cost change based on the specific site remoteness and service rates. Of the two RE technologies, solar PV has a lowest overall cost and no need for crane transportation, which, as discussed in the next section, may compensate for its lower CF, under certain conditions.

4.3.3 RE Scenarios

The wind and solar CFs at KLFN are estimated to be 33% and 12%, respectively. The wind CF might be overestimated due to the lack of on-site wind data; regardless, the WT can be considered to have a significant energy output advantage over the solar resource. In contrast, the solar technology has a lower installation and O&M costs that can potentially justify the investment. Thus, the following six scenarios have been designed to analyze the deployment of both technologies at KLFN: the first set of scenarios (wind, solar, and wind and solar technologies) considers 7% to 9% RE penetration levels that do not require any advanced control systems, whereas the second set increases the RE penetration to 18%, requiring additional energy management considerations. Furthermore, the latter set of scenarios is analyzed considering first only the WT equipment, then WTs with a battery storage system, and finally WTs with an additional 250 kW diesel engine.

Table 4.2: Estimated installation costs of RE equipment at KLFN.

Capital expense	Small WT		Solar PV		Battery bank	
	(\$/kW)	%	(\$/kW)	%	(\$/kWh)	%
Equipment	7,289	53	3,700	44	348	54
Installation	1,709	13	1,840	22	48	7
P.Mgmt. ¹	605	5	600	7	-	-
Logistics	639	5	653	8	134	21
Crane Op.	640	5	-	-	-	-
Spare parts	900	7	554	7	40	6
Contingency	1,632	12	1,019	12	80	12
Total	13,414	100	8,365	100	650	100
	(\$/kW/year)	%	(\$/kW/year)	%	(\$/kWh/year)	%
O&M cost ²	335	2.5	42	0.5	13	2.0

¹P.mgmt. cost for battery bank are assumed to be included in the PV and/or wind project. ²Percentage of capital expense.

The aforementioned scenarios are studied using the estimated costs presented in the previous subsection, and simulated using HOMER, following the above-described dispatch strategy [32]. The objective of the simulation is to find for each scenario the optimal equipment configuration that maximizes the IRR of the RE-based systems, while maintaining the required RE penetration level. This optimization process requires post-processing of the capital and O&M results from the potential RE projects and fuel savings generated when comparing the RE project to the current operation considering only diesel generators. These costs and savings are then used to calculate the IRR for each of the potential projects. The additional project parameters used are: a discount rate of 8%, a project lifetime of 15 years, and the actual electric load profile for 2007. For all scenarios the expected installation and O&M costs, as well as the financial feasibility of RE systems considering the remoteness of KLFN are analyzed, comparing the economic savings to the project baseline, which in this case is the current system solely operating with three diesel generators.

4.3.3.1 Low-Penetration RE-Diesel System

The objective of the first set of scenarios is to obtain the optimal equipment configuration that maximizes the IRR considering a low-RE-penetration system in which the diesel en-

gines are in continuous operation, and at any 1-hr time interval, the RE contribution would not be higher than 50% of the total load. Scenario A considers wind energy, Scenario B analyzes solar energy, and Scenario C studies a wind and solar hybrid system. The RE components aim to reduce the diesel generator share and, as a direct consequence, reduce the diesel-fuel consumption and O&M costs. The low penetration level allows for the installation of standard equipment without the need for elaborate controls to handle RE variations [126]. The RE sizing criterion is to maintain average and 1-hr RE penetrations of less than 20% and 50%, respectively, as illustrated in Figure 4.3, thus avoiding the need for any type of storage or dump load strategy.

Scenario A considers a WT rating search space from 0 to 250 kW of WT installed capacity, considering the operation of only one diesel engine at a time. The resulting RE system with the lowest O&M costs for the given constraints consists of two 50 kW WTs (100 kW). The annual RE contribution can be estimated at 7%, with a capital cost of \$1.34m, and savings of \$0.13m/year with respect to the baseline, which results in an IRR of 6.5%.

Scenario B considers a PV rating search space from 0 to 500 kWp of PV installed capacity, considering the operation of only one diesel engine at a time. The resulting RE system with the lowest O&M costs for the given constraints consists of 250 kWp solar PV. The annual RE contribution can be estimated at 7%, with a capital cost of \$2.09m, and savings of \$0.20m/year with respect to the baseline, which results in a IRR of 6.3%. It should be noted that the RE penetrations and IRR values for Scenarios A and B are close to each other; however, the initial investment is 56% higher for the PV installation, since it requires more installed capacity to deliver the same RE penetration level.

Scenario C combines both RE technologies considering the previous rating search spaces for WT and PV to analyze a hybrid system. The minimum O&M cost system consists of one WT (50 kW) and 200 kWp of solar PV. The annual RE contribution can be estimated at 9%, with a capital cost of \$2.34m, and savings of \$0.22m/year with respect to the baseline, which results in an IRR of 6.4%. Scenario C has the highest RE penetration while still maintaining the 1-hr RE penetration below 50%; however, the required initial investment for such installation is 75% higher than that of Scenario A.

The three low RE penetration scenarios present similar financial results (IRR and NPV); nevertheless, the wind energy option presented in Scenario A offers the lowest capital investment for the required RE penetration level. For this reason, wind energy is selected for the analysis of the medium-RE-penetration scenarios, since funds for capital investments are difficult to secure in RCs.

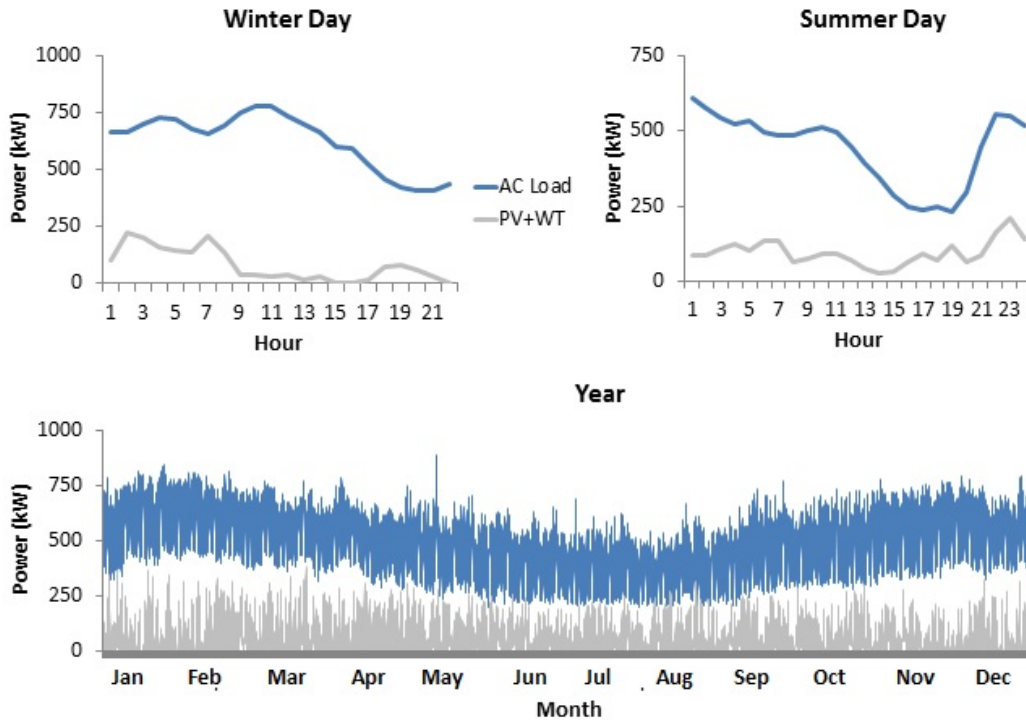


Figure 4.3: Annual/daily power generation and RE contribution in low-penetration scenario.

4.3.3.2 Medium Penetration Wind-Diesel Systems

The objective of the second set of scenarios is to obtain the optimal equipment configuration that maximizes the IRR considering a medium-RE-penetration system, with only WT and batteries. This system would require a more advanced control system to deal with the RE uncertainty, and a dispatch strategy for the WT-diesel operation [126].

Three scenarios are studied that consider a wind energy installation. Scenario D considers a no-cost dump load solution that handles the wind excess energy. Scenario E considers in addition the installation of a small diesel engine to supply the smaller energy gap between the load and the generated wind energy; this small diesel engine serves the purpose of operating at higher efficiencies under high RE penetration levels and low load conditions. Scenario F considers the addition of a battery bank to manage the excess energy without a dump load. The RE sizing criterion is maintaining an average and 1-hr RE penetration of less than 20% and approximately 100%, respectively [126], as shown in Figure 4.4.

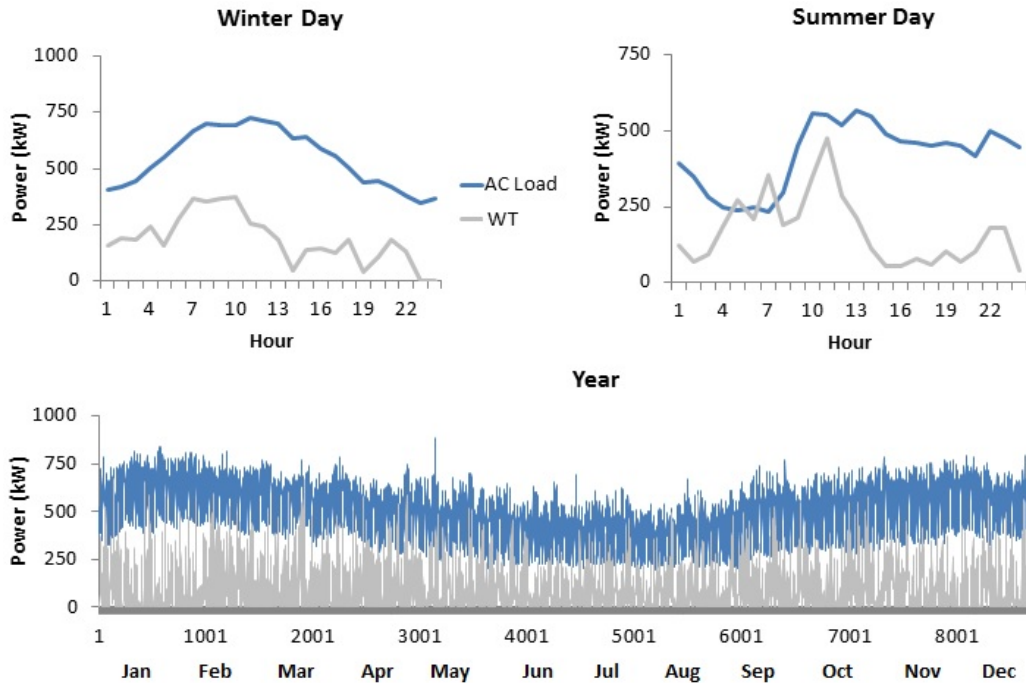


Figure 4.4: Annual/daily power generation and RE contribution in medium-penetration scenario.

For Scenario D, the WT rating search space is from 0 to 500 kW of installed capacity, considering the operation of only one diesel engine at a time. The resulting RE system with the lowest O&M costs for the given constraints is composed of five 50 kW WTs (250 kW). The annual RE contribution is estimated at 18%, with a capital cost of \$3.35m and savings of \$0.31m/year with respect to the baseline, which results in an IRR of 5.6%, which is lower than that of the low penetration case (7%). Scenarios E and F are considered to verify if the extra capacity and storage can be used to improve the financial outcome of the project.

Scenario E sets the WT capacity at 250 kW and considers a small diesel engine in the 50 kW to 300 kW range, so as to avoid running higher capacity engines at a low efficiency, thus increasing dispatch flexibility for low-load periods. The diesel engine installation cost is calculated following the same methodology as for the RE equipment, resulting in an installation cost of \$2,400/kW. The simulation yields an optimal size of 250 kW for the new diesel engine, considering a total capital expense (WT + diesel engine) of \$4.10m and savings of \$0.34m/year with respect to the baseline, which results in an IRR of 4.0%, which is lower than those of the low-RE-penetration Scenarios and Scenario D.

Scenario F keeps the WT capacity at 250 kW and considers a battery bank in the 27 kWh to 137 kWh range, with a 50% maximum depth of discharge. The minimum O&M cost is attained with a battery bank of 54.8 kWh nominal capacity (27 kWh usable capacity). The obtained capital cost is \$3.53m, with savings of \$0.33m/year with respect to the baseline, which results in an IRR of 3.7%, which is the lowest value of all presented scenarios.

4.3.4 Discussion

The results from the analysis of the baseline, low-RE-penetration, and medium-RE-penetration scenarios are summarized in Table 4.3. The first section of the table presents the main characteristics of the systems considered, including the RE installed capacity selected. The second section in the table presents the estimated annual fuel consumption savings and obtained CO₂ emission reductions. The remaining sections summarize the capital and O&M costs, as well as relevant financial indicators. Observe that the IRR values for the medium-RE-penetration scenarios are lower than those for the low level scenarios, which is a result of the excess energy that does not further reduce operating costs (Scenario D), and the high installation costs of batteries and the small diesel engine that reduce operating costs but not enough to justify the additional investment (Scenarios E and F).

The wind and solar low-RE-penetration alternatives result in similar return on investment (6%). Wind power results in higher RE penetration levels with lower capital investments, while solar power requires approximately 50% higher investment, but due to the low O&M costs of solar PV, the obtained financial results are comparable. The wind medium-RE-penetration scenarios have a lower return on investment, due to the FGs operating at lower efficiencies and the wind excess energy not further reducing operating costs. The addition of a battery bank or a small diesel engine partially alleviates these issues; however, the extra capital investment does not have a positive economic effect.

From the overall results in Table 4.3, one can conclude that none of the scenarios are economically feasible based on the resulting NPV and IRR values. The NPVs values are negative which means that based on a 8% discount rate none of the projects are able to generate sufficient income to overcome the capital and O&M expenses. Furthermore, the obtained IRR corroborate the NPV results since all values are below the standard discount rate of 8%. The main reasons behind these results are the high capital costs and the modest RE resources in the community. Nevertheless, this research shows that RE alternatives in the community are close to breaking even given the current conditions. Furthermore,

as shown in Chapter 5, more detailed analysis and adequate modelling due to additional constraints lead to other economically feasible alternatives not considered in this chapter.

4.4 HOMER limitations

In this chapter, HOMER was selected due to its adequacy to analyze RE projects in isolated microgrids; however, as any software tool, HOMER has certain limitations when considering some of the aspects of RC electricity operation, such as:

- *Single customer type*: HOMER allows for the analysis of only one community electricity price, which in the software is related to the diesel fuel price. However, in RCs, there is usually different types of customers that pay significantly different electricity rates; hence, the feasibility of such projects is subject to the different rates.
- *Single operation schemes*: HOMER assumes that the studied RE capacity is used to cover the total electricity demand. However, in practice a subset of the RE equipment could be operated to cover a certain load under a Self-Consumption (SC) or Net-Metering (NM) agreements, affecting the RE equipment operation. These SC and NM projects are likely to co-exist in a community with RE projects under a Power Purchase Agreement (PPA) in which the electricity is injected directly to the microgrid.
- *One year project deployment*: HOMER assumes that the RE project is deployed during the first studied year, and does not allow for a multiple-year deployment horizon. However, a multiple year plan can give a community an advantage, since it is likely to reduce the capital costs within the investment years.
- *Cost reduction as a function of RE capacity*: HOMER does not consider the potential of capacity building as more RE technologies are installed in the community over the years. Since HOMER analyzes one project event at a time, this tool cannot adjust the equipment deployment costs as a function of a set of planned RE projects over a multi-year horizon.
- *Lack of flexibility*: HOMER has improved over the years, adding more equipment, operation strategies, and constraints alternatives. However, the software does not have flexibility to add user-defined constraints or evaluating criteria other than NPV.

Table 4.3: Summary table for KLFN low- and medium-RE-penetration scenarios.

	Units	Baseline	Low RE pen. ¹			Medium RE pen. ²		
			A	B	C	D	E	F
Syst. Characteristics								
Annual RE con-tribution	%	-	7	7	9	18	18	18
Hourly max. RE penetration	%	-	49	53	50	123	123	123
Diesel Eng.	No.	3	3	3	3	3	4	3
PV installed	kW	-	-	250	200	-	-	-
WT installed	kW	-	100	-	50	250	250	250
Storage capacity	kWh	-	-	-	-	-	-	27
Fuel/emissions								
Annual fuel	Mlt	1.07	1.00	0.99	0.97	0.91	0.89	0.90
Fuel reduction ¹	Mlt	-	0.07	0.08	0.10	0.16	0.18	0.17
	%	-	6.5	7.5	9.3	15.0	16.8	15.9
Emissions	Mton	3.33	3.11	3.08	3.02	2.83	2.77	2.80
Capital costs								
Solar energy	\$m	-	-	2.09	1.67	-	-	-
Wind energy	\$m	-	1.34	-	0.67	3.35	3.35	3.35
Storage	\$m	-	-	-	-	-	-	0.18
Diesel engine	\$m	-	-	-	-	-	0.75	-
Total	\$m	-	1.34	2.09	2.34	3.35	4.10	3.53
Annual O&M costs								
Expense	\$m	3.68	3.55	3.48	3.46	3.38	3.35	3.35
Reduction ³	\$m	-	0.13	0.20	0.22	0.31	0.34	0.33
Financial indicators								
NPV ⁴	\$m	-	-0.11	-0.19	-0.20	-0.44	-0.87	-0.79
IRR	%	-	6.5	6.3	6.4	5.6	4.0	3.7

¹Low RE penetration: (A) Wind, (B) Solar, and (C) Solar + wind.

²Medium RE penetration: (D) No cost dump load, (E) Scenario D + small diesel engine, and (F) Battery bank with no dump load.

³Compared to baseline.

⁴NPV of the total project cost at an 8% discount rate.

As a result, it is not possible to modify the model to consider certain RE unique characteristics, as the ones previously mentioned. At this time, the only option available is to conduct a post-processing analysis of the HOMER results to account for these additional issues.

The next chapter addresses these limitations of HOMER by considering a comprehensive objective function and various relevant constraints through the development and solution of an RE generation planning mathematical model.

4.5 Summary

This chapter discussed and presented a methodology to evaluate the possible integration of RE technologies in Ontario's RCs. A customized analysis of RE equipment and deployment costs was also presented to evaluate RE projects in remote locations, using the KLFN community as a reference. Six case studies were presented for this community, analyzing the economic feasibility of three low-RE-penetration scenarios (7%–9%) and three medium-RE-penetration scenarios (18%).

It was shown that the RE installation cost can be as high as 2.5 times that of an equivalent on-grid system. Furthermore, given the current deployment conditions, it was concluded that RE deployment in the KLFN community is not economically feasible, given the high capital investments required. However, as it is discussed in the next chapter, more adequate modelling due to additional constraints and alternative funding considerations for the RE deployment problem can result in feasible alternatives for the community.

The content of this chapter has been published in [104].

Chapter 5

Mathematical Programming Approach for Microgrid RE Generation Planning

This chapter presents a novel LTRGP model for RCs, considering the characteristics of diesel-based RCs in Canada. The proposed model creates a multiple-year community planning tool that can be used to determine economic and technically-feasible RE solutions, considering the current operating structures, electricity pricing systems, subsidy frameworks, RE resources, and project funding alternatives.

The chapter initially analyzes the types of customers described in Chapter 3 and matches them to operating frameworks in which RE projects can be implemented in RCs. Then, the proposed mathematical model for the LTRGP problem is presented, covering the required input information, forecasts, equipment models, and optimization problem solutions. Finally, the chapter presents a case study developed in collaboration with KLFN, and discusses the results applying the proposed multiple-year RE plan for various alternative scenarios.

5.1 Electricity Rates and Subsidies

As part of a long-term RE energy plan, community Applicable Electricity Rates (AERs) need to be understood in order to assess the potential benefit of RE projects in RCs. AERs in Canada vary significantly depending on the subsidy level which generally aims to set electricity prices for off-grid residents at par with the on-grid counterpart rates [94]. The

details and subsidy levels differ by location; however, from the available information, the following generalized rate classification can be used:

- *Unsubsidized Customer (UbC)*: These customers pay approximately the actual cost of electricity since they do not receive a direct subsidy. These rates apply mainly to federal government clients and some community-owned buildings. This type of customers can install and some have installed RE equipment for SC purposes.
- *Subsidized Customer (SbC)*: These customers pay prices that match the electricity rates of southern locations for provinces and capitals for territories. In general, these rates apply to residential customers, and are approximately 10% to 20% of the actual electricity cost. Due to the highly subsidized tariff, RE is not likely to be economically feasible for these customers.
- *Avoided Fuel Cost (AFC)*: This rate does not refer to an RC customer type, but to the fuel displacement cost resulting from electricity generation, including administration and transportation costs. Hence, the AFC ultimately represents the energy cost that RE projects compete against. The rate is approximately 40% to 60% of the energy cost depending on the RC location. A PPA can be established with the utility to generate RE power, fixing the rate to the AFC.

The AERs are closely related to the different operation schemes, i.e., customers, under which RE projects have been or can be deployed in RCs within the current utility/community operating structures. Table 5.1 summarizes the AERs, and operation schemes, highlighting the advantages and disadvantages of each scheme. Similar rate structures exist in other parts of the world (e.g., [127]).

5.2 Planning Mathematical Model

One of the main objectives of this thesis is to develop a multiple-year RE planning model that can help RCs determine the feasibility of projects considering the characteristics of remote microgrids. Hence, the model presented here aims to maximize the potential benefit or social welfare W perceived by the community, while identifying:

- RE equipment type and capacity to be deployed.

Table 5.1: RE operation schemes and customer types for remote communities

Scheme	AERs ¹			Advantages	Disadvantages
	UbC	AFC	SbC		
Utility-owned		X ²		Simple ownership structure. Simpler deployment logistics and equipment O&M.	No community involvement required. Potentially no economic benefit to the community.
PPA ³		X		Community can be sole-owner or partner. Significantly higher RE export compared to NM.	Negotiation of an export rate that benefits all involved parties can be cumbersome. RE deployment costs need to decrease to achieve economic feasibility, attainable in the medium-term.
SC ⁴	X			Community-owned buildings can have immediate savings without a PPA. Closest type of projects that can reach economic feasibility.	Limited load to be served under these scheme ($\approx 10\%$ of community demand). For safety purposes, RE unit(s) shut-down when exporting RE to the microgrid.
NM ⁵	X			Increased benefit when compared to SC due to microgrid energy export.	Limited load to be served under these scheme ($\approx 10\%$ of community demand). Requires NM agreement with utility; however, energy export is not likely to justify agreement related costs.
SC ⁴			X	Program can be extended to all residential customers.	Unrealistic to generate RE at cost lower than the subsidized rate.
NM ⁵			X	Increased benefit when compared to SC due to microgrid energy export.	Requires NM agreement with utility; however, energy export is not likely to justify agreement related costs.

¹ Applicable electricity rate.

² X denotes the applicable AER for the selected operation scheme.

³ Power purchase agreement.

⁴ Self-consumption.

⁵ Net-metering.

- Operation schemes under which RE units can operate.
- Installation time-frame for RE equipment.
- RE equipment location for customers whose current load demand is known.

The model significantly benefits from the energy-related information that can be obtained for most RCs in Canada since such locations currently have access to electricity [10, 94]. Such information includes the existing operating structure, generation equipment, customer classification, RE resources, and subsidy framework that help create a model that closely portrays the RE planning problem in RCs. However, up-to-date detailed information is not readily available and also requires close collaboration with the involved stakeholders, i.e., communities, utilities, government agencies, and project planners.

5.2.1 Model Architecture

Figure 5.1 shows the structure of the proposed model, which is composed of four stages: The input data stage (Stage I) includes historical data for natural resources, community location and energy-related information, and FG and RE equipment specifications. The forecast stage (Stage II) creates the time-series estimates for the electric load, and the on-site RE resources for the planning horizon. The pre-processing stage (Stage III) calculates the dispatch strategy details for FGs, estimates the power profile, pre-selects configuration details for each RE equipment type, and overall generation costs. Finally, the optimization stage (Stage IV) solves a proposed MINLP problem that maximizes the RE planning social welfare for the community. It is important to note that, based on [28, 82], battery energy storage is not considered as a viable alternative in the proposed model, since under the current conditions, battery energy storage for RCs present several challenges such as thermal management and investment and O&M costs, that do not make it a feasible option in the medium term, as previously discussed in Section 2.2.3.

Optimal sizing and placement of DG units has been a widely researched topic in on-grid and, to a lower extent, in off-grid systems (e.g., [34, 128]). The technical advantages of such methodologies have been clearly identified, such as reduction of system losses and/or improved stability of the system. However from a practical perspective, the technical improvements are not likely to be a decisive consideration for most RE planning processes in RCs. In general, the most important considerations are the previously-described AERs

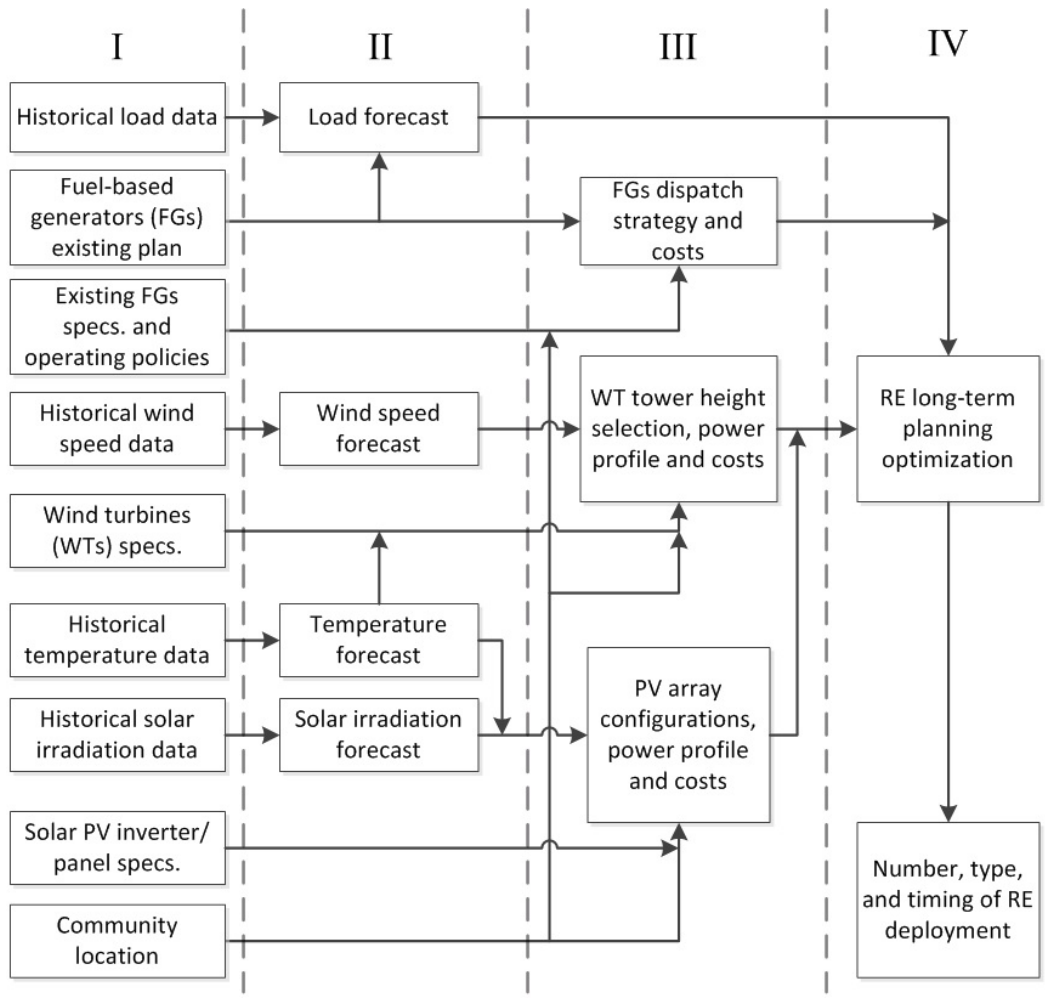


Figure 5.1: Mathematical model architecture.

rates and the social and land-management issues of the community; nevertheless, as it is discussed below, the RE sizing and placement problem is dealt with in the proposed LTRGP model.

5.2.2 Stage I: Historical Data and Equipment Specifications

5.2.2.1 Load and Installed Equipment

Detailed historical information for the majority of RCs is available from off-grid utilities, once a community gives access to such information. The minimum data requirements for the proposed model are the hourly electricity generation time-series and the annual electricity demand growth rate. In some cases, seasonal growth rates are preferred due to the wide load variations throughout the year. In addition, electricity consumption for large individual customers, if available, can be included in the RE planning model.

Most RCs have a 3-5 fuel-based engine unit configuration, with the sizes depending on the operation strategy of the utility. Some utilities operate the units in parallel, where the diesel generators have similar rated capacities, and others operate mainly using a single-unit strategy, with the diesel generators having different rated capacities ranging from the expected minimum to the maximum load of the community [94].

5.2.2.2 RE Resources

The solar irradiation, temperature, and wind speed resources used in the proposed model are based on the information presented in Section 3.7, which provides a time-series with 1-hr resolution and historical data for approximately 7+ years for most RCs in Canada. However, data sources for such locations do not typically include on-site ground data; thus, this issue needs to be considered as part of the planning problem. Therefore, for solar irradiation data, which presents limited correlation between satellite and ground data for northern latitudes, the accuracy of the available data decreases by approximately 10% to 15% [129]. For wind speed data, the limited available studies give a significant wind speed range for northern locations, with the difference being greater than ± 0.5 m/s annual average, which translates into $\pm 10\%$ deviation for some locations [108]. In the proposed model, these variations are dealt with by creating scenarios that consider the value range for the resources.

5.2.3 Stage II: Forecasts

5.2.3.1 Electric Load

A multiple-year hourly historical data can be used to create a load forecast that follows the current load profile in the community. Thus, a forecast of the annual energy growth rate can be obtained by using the historical data available, assuming that the energy growth rate has a normal distribution function. This forecast energy growth is then used to scale the historical time-series information for the total planning horizon. However, this growth rate is subject to the limits described in Section 3.6.

5.2.3.2 Solar Irradiation and Temperature Forecasts

In a similar way to the case of the electric load forecast, the solar and temperature forecasts are obtained by scaling the hourly historical data by assuming a normal distribution of the annual average value for the respective parameters. In most cases, available data covers 10 years or more; hence, a representative data sample can be used to create these forecasts. Figure 5.2 shows an example of the solar irradiation fit using a normal distribution for KLFN; this data is used in the case studies presented in this chapter.

5.2.3.3 Wind Speed Forecast

This forecast can be obtained following the previously-described simple forecast method; however, in some instances, historical data might be limited. In such cases, synthetic wind speed time-series can be used to create the respective forecast [130, 131]. Thus, the methodology proposed in [130] is followed here to create the respective time-series data. The technique is based on a Markov chain process that creates a possibility matrix representing wind speed transitions, or likelihood, of the wind speed to change from ws_1 to ws_2 at the defined time resolution. With this approach, the wind speed forecast is generated assuming a normal distribution for wind speed annual averages. Figure 5.3 shows an example of the this normal distribution fit for annual wind speed averages for KLFN; as in the case of the solar irradiation data previously mentioned, this data is used in the presented case studies.

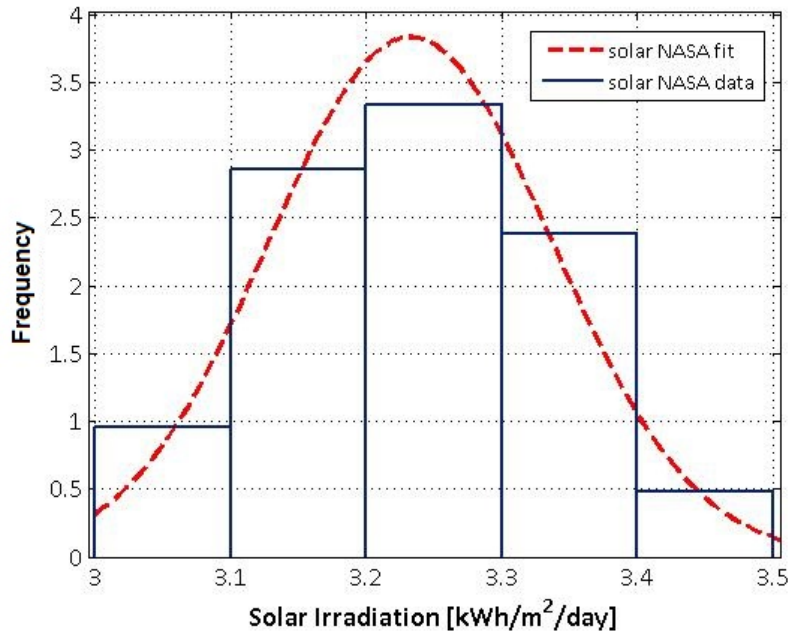


Figure 5.2: Normal distribution fit example for annual solar irradiation averages for KLFN.

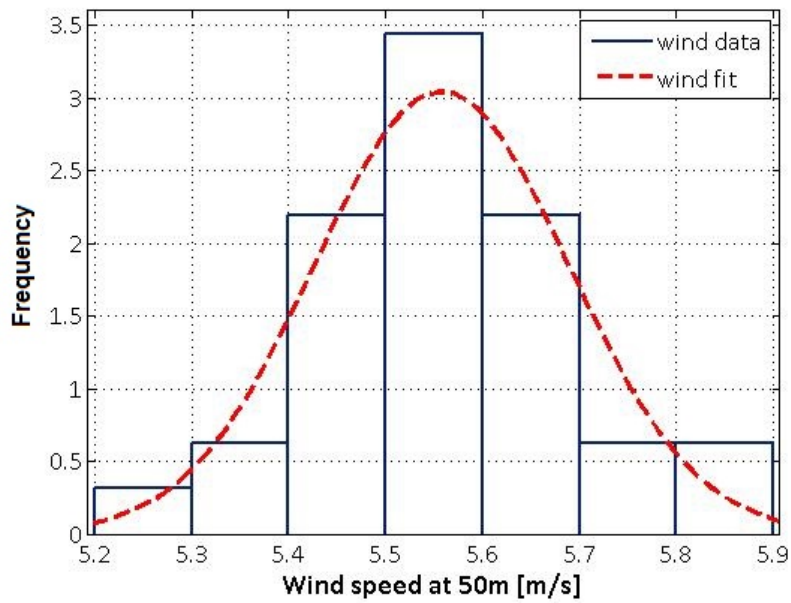


Figure 5.3: Normal distribution fit example for annual wind speed averages for KLFN.

5.2.4 Stage III: Generation Equipment Considerations

The proposed LTRGP model requires electricity generation equipment calculations that precede the optimization step. The calculations include the dispatch strategy details for FGs and on-site available power, and Levelized Cost of Energy (LCOE) for the RE equipment under consideration, as explained next.

5.2.4.1 Fuel-based Generators

The unit commitment and dispatch problem for FG facilities in RCs is trivial when compared to large systems, simply because of the limited installed capacity and consequently less operating alternatives [68]. In this work, the dispatch strategy and spinning reserves are determined by the operating limits of the generators, which is programmed in the generators' Programmable Logic Controllers (PLCs). The PLCs' limits and setpoints keep approximately 15% spinning reserve margin, committing units based on the generators' rated capacity vis-a-vis the demand, under normal operating conditions. Therefore, the unit commitment for the single-FG dispatch strategy is given by:

$$P_{FG_{j,t,h}} = \begin{cases} P_{FG_{t,h}} & \text{if } p_{j,t}^{\min} \leq P_{FG_{t,h}} < p_{j,t}^{\max} \quad \forall j \\ 0 & \text{otherwise} \end{cases} \quad (5.1)$$

where $P_{FG_{t,h}}$ is the power required from the plant, and $P_{FG_{j,t,h}}$ is the output power of generator j . In addition, $p_{j,t}^{\min}$ and $p_{j,t}^{\max}$ are the following pre-determined minimum and maximum operating setpoints for each FG:

$$p_{j,t}^{\min} = \begin{cases} d_{GS}^{\min} RP_j s_{j,t} & \text{if } j = 1 \\ p_{j-1,t}^{\max} s_{j,t} & \text{if } j = 2, \dots, J \end{cases} \quad (5.2)$$

$$p_{j,t}^{\max} = \begin{cases} d_{GS_1} RP_j s_{j,t} & \text{if } j \text{ to } j+1 \text{ turns on} \\ d_{GS_2} RP_j s_{j,t} & \text{if } j \text{ to } j-1 \text{ turns on} \end{cases} \quad (5.3)$$

where d_{GS}^{\min} is the minimum load ratio at which FGs run in normal operating conditions; RP_j is the nominal power for FG; and $s_{j,t}$ is a pre-defined binary parameter which defines if the FG is operating in year t , as per a utility/community FG deployment plan. Additionally, $d_{GS_{1,2}}$ represents the two FG conditions when switching between units; when unit j switches to $j+1$, d_{GS_1} is the nominal FG power minus the spinning reserve, i.e., 85%,

and when j switches to $j - 1$, d_{GS_2} is set to a lower ration than d_{GS_1} , i.e., 75%-80%. The latter yields a hysteresis model to represent waiting until the load has fallen below the spinning reserve limit of unit $j - 1$, before starting up this unit, thus reducing the number of engine start-ups, while dealing simultaneously with the spinning reserve problem.

5.2.4.2 RE Reduced Search Space

In Stage III in Figure 5.1 pre-processing of the available RE equipment information is carried out. This is based on a power output calculation for all RE equipment, and an equipment pre-selection process that reduces the search space to be used in the main optimization problem in Stage IV.

The RE power output for the solar PV and WT equipment considered are calculated following the procedure and equations described in Section 2.2. Thus, both solar PV and WT power outputs are corrected for temperature variations, and the required equipment specifications for the respective equipment models are obtained from the manufacturers' data sheets.

The RE reduced search space process aims to reduce the computational time of the main optimization problem by pre-selecting equipment configurations that better fit the community location. In the case of solar PV module, this process consists on selecting solar PV arrays that best match the available inverters to minimize costs, as opposed to just considering individual solar PV panels. In the case of WT module, the pre-selection process consists on matching each WT to the most cost-effective WT tower height.

For each type of solar PV and WT equipment considered, the most cost-effective configuration is obtained by calculating the widely-used LCOE $LC_{k,g}$ given by:

$$\min \quad LC_{k,g} = \frac{C_{TEQ_{k,g}}}{\sum_{t=1}^{ELT_k} \frac{\sum_{h=1}^H P_{REM_{k,g,t,h}}}{(1+RD)^t}} \quad (5.4)$$

where $C_{TEQ_{k,g}}$ represents the NPV for the capital and O&M cost; ELT_k is the equipment operating lifetime; RD is the discount rate; and $P_{REM_{k,g,t,h}}$ is the RE power calculated from the wind and solar equipment models, described next.

Solar PV Equipment Pre-selection

The solar PV pre-selection process creates feasible cost-effective solar arrays for each type of PV module type, considering the available inverters and their operating constraints such as currents and voltages, and yields the corresponding power output profiles. The main objectives are identifying the best PV array configuration for each module type and, at the same time, reducing the search space for the optimization process. Such pre-selection is done by estimating the solar PV array total cost, given by:

$$C_{TEQ_{k,g}} = \left(C_{PVU_k} + \sum_{t=1}^{ELT_k} \frac{C_{PVOM_k}}{(1+RD)^t} \right) x_{PVP_{k,g}} x_{PVS_{k,g}} + C_{PVINV_g} \quad (5.5)$$

where C_{PVU_k} and C_{PVINV_g} are the PV module and inverter cost, respectively; C_{PVOM_k} is the annual O&M cost per module; and $x_{PVP_{k,g}}$ and $x_{PVS_{k,g}}$ are the variables representing the numbers of PV modules in parallel and series for each array. The RE power output for the solar PV modules, $P_{REM_{k,g,t,h}}$ in (5.4), is determined based on the model described in Section 2.2.1.

The LCOE minimization process for the array configuration is, in addition, subject to:

$$\begin{aligned} I_{PV_{k,t,h}} x_{PVP_{k,g}} &\leq I_{PVINV_g}^{\max} \\ V_{PVINV_g}^{\min} &\leq V_{PV_{k,t,h}} x_{PVS_{k,g}} \leq V_{PVINV_g}^{\max} \\ P_{PV_{k,t,h}} x_{PVP_{k,g}} x_{PVS_{k,g}} &\leq P_{PVINV_g}^{\text{nom}} \\ x &> 0 \\ x &\in \mathbb{Z} \end{aligned} \quad (5.6)$$

where $I_{PV_{k,t,h}}$, $V_{PV_{k,t,h}}$ and $P_{PV_{k,t,h}}$ are the output current, voltage, and power of the PV array, respectively; $I_{PVINV_g}^{\max}$ and $V_{PVINV_g}^{\max}$ the current and voltage ratings of the inverter; and $P_{PVINV_g}^{\text{nom}}$ is the inverter power rating.

Wind Turbine Equipment Pre-selection

The WT pre-selection process is based on calculating the wind speeds at different heights and determining the total deployment cost. Thus, the WT total cost given by:

$$C_{TEQ_{k,g}} = C_{WTU_k} + C_{WTTWR_{k,g}} + \sum_{t=1}^{ELT_k} \frac{C_{WTOM_k}}{(1+RD)^t} \quad (5.7)$$

where C_{WTU_k} and $C_{WTTWR_{k,g}}$ are the equipment cost for the WT and tower, respectively, and $C_{WTO_{M_k}}$ is the O&M annual cost for each turbine.

The WT output power calculation used here follows the small WT guidelines from the IEC 61400 standards, and considers the air density and hub-height for each location and WT type, respectively, as per the equations described in Section 2.2.2. In addition to the previously-described WT model, the temperature in northern Canada varies in a wide range and needs to be considered as part of the pre-selection process; this effect can be included by means of the following constraint:

$$P_{WT_{k,g,t,h}} = \begin{cases} P_{WTDC_{k,g,t,h}} & \text{if } TM_{WT_k}^{\min} \leq TM_{t,h} \leq TM_{WT_k}^{\max} \\ 0 & \text{otherwise} \end{cases} \quad (5.8)$$

where $P_{WTDC_{k,g,t,h}}$ is the WT power output obtained from (2.3) or (2.6), depending on the WT speed control mechanism; $TM_{t,h}$ is the hourly average temperature; and $TM_{WT_k}^{\min}$ and $TM_{WT_k}^{\max}$ are the lower and upper temperature limits for the WT under consideration, respectively.

5.2.5 Stage IV: RE Long-term Planning

5.2.5.1 Objective Function

The LTRGP model is an MINLP problem that maximizes the benefit to the RC, given the deployment and operating constraints of such locations. Hence, the optimization problem is defined as follows:

$$\max \sum_{i=1}^I \sum_{t=1}^T \frac{W_{i,t}}{(1 + RD_i)^t} \quad (5.9)$$

where

$$W_{i,t} = IS_{i,t} - C_{i,t} - LR_{i,t} \quad (5.10)$$

with $IS_{i,t}$ referring to the direct income and/or savings obtained from deploying RE equipment, $C_{i,t}$ comprises to the associated project costs incurred through the planning horizon, and $LR_{i,t}$ refers to direct community economic losses encountered as a consequence of RE deployment. These variables consider the RE economic impact for different customers.

5.2.5.2 Income and Savings

As described in Section 5.1, AERs change significantly among customer types and, therefore, these have a significant effect on potential RE deployments. For example, in the case of SbC which pay the highest electricity rates, RE projects will generate a savings for the specific customer. In the case of PPA related projects, the objective is to generate an income from selling electricity to the utility. Thus, the income/savings component of (5.10) is:

$$IS_{i,t} = (CD_i(1 + r_i)^t + INC_i) \sum_{k=1}^K \sum_{h=1}^H P_{REu_{i,k,t,h}} \quad (5.11)$$

where CD_i is the present electricity rate; r_i is the respective annual price change; INC_i an external energy incentive, if available; and $P_{REu_{i,k,t,h}}$ is the renewable power used to supply the load, as defined later in this section.

5.2.5.3 Capital and O&M Costs

The project costs $C_{i,t}$ comprise initial capital contributions, financial/loan, and O&M costs throughout the projects' lifetime, and is given by:

$$C_{i,t} = \sum_{k=1}^K (C_{CE_{i,k,t}} + C_{BPMT_{i,k,t}} + C_{OM_{i,k,t}}) \quad (5.12)$$

where $C_{CE_{i,k,t}}$, $C_{BPMT_{i,k,t}}$, and $C_{OM_{i,k,t}}$ are described in detailed next.

Initial Capital Expenses

The parameter $C_{CE_{i,k,t}}$ is defined as follows:

$$C_{CE_{i,k,t}} = C_{CAP_{i,k,t}} b_{CEP} (1 - b_{EFP}) \quad (5.13)$$

$$C_{CAP_{i,k,t}} = RC_{CAP_k} RP_k CB_{k,t} x_{i,k,t} \quad (5.14)$$

where b_{CEP} and b_{EFP} are the percentage of available capital contribution at the start of the project, and the percentage of available external funding with respect to the total project cost, respectively; RC_{CAP_k} is the present equipment cost per kW; RP_k is the equipment

rated capacity; $x_{i,k,t}$ is the number of RE units to be deployed; and $CB_{k,t}$ is the CB factor. The latter represents the installation learning curve likely to be experienced at the community as more RE units are deployed, which is modelled by linearly reducing the deployment costs as additional similar units are installed; such cost reduction continues until a pre-defined minimum limit is reached, which represents a realistic reduction in installation costs in the medium-term. This factor is thus defined as:

$$CB_{k,t} = \begin{cases} b_{CBm}EQC_{k,t} + b_{CBb} & \text{if } EQC_{k,t} \leq b_{CBu} \\ b_{CB}^{\max} & \text{otherwise} \end{cases} \quad (5.15)$$

where

$$EQC_{k,t} = \sum_{i=1}^I \sum_{v=1}^T x_{i,k,t} \quad (5.16)$$

with b_{CBm} and b_{CBb} being the linear and constant cost reduction coefficients, respectively; b_{CB}^{\max} is the maximum cost reduction allowed; and b_{CBu} is the number of units at which b_{CB}^{\max} is reached. The capacity building coefficients b_{CBm} and b_{CBb} are defined as:

$$b_{CBm} = \frac{-b_{CB}^{\max}}{b_{CBu} - 1} \quad (5.17)$$

$$b_{CBb} = 1 - b_{CBm} \quad (5.18)$$

The available project capital ratio b_{CEP} in (5.13) is likely to be modest, since current Aboriginal Band budgets are typically dedicated to higher priority issues, such as education, health, and infrastructure. Thus, if an RC engages in RE projects, it would require to seek external federal or provincial government funding [132, 133], as well as financing instruments through, for example, bank loans, with the latter having two main positive effects from the RE project perspective: increases the community's real and perceived project ownership and creates a higher level of O&M responsibility due to the required periodic bank loan payment schedule.

External Funding

The external funding parameter $C_{BPMT_{i,k,t}}$ in (5.12) refers to the amortization payment

given by:

$$C_{BPMT_{i,k,t}} = C_{BL_{i,k,t}} \frac{r_B(1+r_B)^{BLT_k}}{(1+r_B)^{BLT_k} - 1} \quad (5.19)$$

where

$$C_{BL_{i,k,t}} = C_{CAP_{i,k,t}} - C_{CE_{i,k,t}} - C_{EF_{i,k,t}} \quad (5.20)$$

$$C_{EF_{i,k,t}} = C_{CAP_{i,k,t}} b_{EFP} \quad (5.21)$$

and the parameter r_B is the bank interest rate, and BLT_k is the total number of loan payments.

O&M Costs

The O&M costs in (5.12) extend through the RE equipment lifetime and are given by:

$$C_{OM_{i,k,t}} = RC_{OM_k} RP_k b_{OM_t} EOS_{i,k,t} \quad (5.22)$$

where

$$EOS_{i,k,t} = eos_{i,k,s} = \sum_{u=1}^T y_{i,k,u,s} \quad (5.23)$$

and

$$y_{i,k,u,s} = x_{i,k,t} \quad \forall \quad s = t, t+1, \dots, t+ELT_k \leq T, \quad (5.24)$$

$$u = 1, 2, \dots, T$$

In (5.22), the parameter RC_{OM_k} is the present O&M cost per kW, b_{OM_t} is the cost variation through the equipment's operating lifetime, which is likely to increase in later years. In addition, $EOS_{i,k,t}$ represents the number of units on-site, and $y_{i,k,u,s}$ is an auxiliary variable relating $EOS_{i,k,t}$ to $x_{i,k,t}$.

5.2.5.4 Loss of Opportunity Cost

Some RCs could experience a potential loss of opportunity cost $LR_{i,t}$ as a direct consequence of RE deployment. This economic loss is incurred if the community is the sole or partial fuel supplier for the utility company, and can be defined as follows based on:

$$LR_{i,t} = r_{FR} C_{FUEL} b_{CFP_t} (1 + CPI)^t (f_{BASE_t} - f_{PROJ_t}) z_{i,t,h} \quad (5.25)$$

where r_{FR} is the percentage of fuel revenue obtained by the community; C_{FUEL} is the actual on-site fuel price; b_{CFP_t} is the percentage of the total fuel supply purchased from the community; CPI is the customer price index fuel price growth; f_{BASE_t} is the fuel consumption of the baseline scenario, i.e., with no RE equipment installed; f_{PROJ_t} is the expected fuel consumption after RE equipment deployment; and $z_{i,t,h}$ is the ratio of RE used for each customer, defined as:

$$z_{i,t,h} = \frac{\sum_{k=1}^K P_{REu_{i,k,t,h}}}{\sum_{i=1}^I \sum_{k=1}^K P_{REu_{i,k,t,h}}} \quad (5.26)$$

The fuel consumption for the baseline and project scenarios in (5.25) are represented by:

$$f_{BASE_t} = \sum_{j=1}^J \sum_{h=1}^H (d_{GSa_j} P_{FG_{BASE_{j,t,h}}} + d_{GSb_j}) \quad (5.27)$$

and

$$f_{PROJ_t} = \sum_{j=1}^J \sum_{h=1}^H (d_{GSa_j} P_{FG_{proj_{j,t,h}}} + d_{GSb_j}) \quad (5.28)$$

where d_{GSa_j} and d_{GSb_j} represent the linear and constant coefficients for fuel consumption vs. power relationship, since the rated power of FGs used in RCs is relatively low (< 2MW).

5.2.5.5 Model constraints

The power per generator for the baseline and project scenarios $P_{FG_{BASE_j,t,h}}$ and $P_{FG_{proj,t,h}}$, respectively, are calculated by:

$$P_{FG_{t,h}} = P_{D_{t,h}} - \sum_{i=1}^I \sum_{k=1}^K P_{REu_{i,k,t,h}} \quad (5.29)$$

where $P_{D_{t,h}}$ represents the community load demand.

There are three categories of RE power used in the proposed planning model: (i) the available RE power P_{REa} , which is the calculated power output from the respective wind and solar model; (ii) the RE used power P_{REu} , which is the expected power to be consumed by the community; and (iii) the curtailed RE power P_{REc} , which is the excess power resulting from the dispatch constraints for RE equipment. These RE-dependant variables are given by:

$$P_{REu_{i,k,t,h}} = P_{REa_{i,k,t,h}} - P_{REc_{i,k,t,h}} \quad (5.30)$$

$$P_{REa_{i,k,t,h}} = P_{REM_{k,t,h}} EOS_{i,k,t} \quad (5.31)$$

$$P_{REc_{i,k,t,h}} = \begin{cases} P_{DB_{i,t,h}} & \text{if } P_{DB_{i,t,h}} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (5.32)$$

where $EOS_{i,k,t}$ is determined in (5.23) and

$$P_{DB_{i,t,h}} = \sum_{k=1}^K P_{REa_{i,k,t,h}} - P_{D_{i,t,h}} + d_{GSLIM_{i,t}} \quad (5.33)$$

$$d_{GSLIM_{i,t}} = (1 - CT_i) d_{GS}^{\min} RP_t^{\min} \quad (5.34)$$

$$P_{D_{i,t,h}} = P_{D_{t,h}} b_{D_i} \quad (5.35)$$

with $P_{DB_{i,t,h}}$ representing the difference between the available renewable power and the respective load; $d_{GSLIM_{i,t}}$ is the FG lower limit at which, when reached, RE is curtailed; CT_i is a pre-defined binary constant used to distinguish between RE curtailment classes, with $CT_i = 1$ representing the case when RE is only for SC (no grid feeding), and $CT_i = 0$ representing the case when RE can inject power to the grid; d_{GS}^{\min} is the minimum FG load

ratio; RP_t^{\min} is the rated power of the smallest FG; and b_{D_i} is the load ratio of the total demand for each customer i where $\sum_{i=1}^I b_{D_i} = 1$. The distinction between curtailments in the model is based on previous RE northern projects. Thus, $CT_i = 1$ involves disconnecting the RE source from the microgrid to avoid sending any power to the distribution system; this has been the case of certain SC projects, since no contract with the utility was in place to allow electricity export (3 SC projects in northern Ontario have been supported in the last few years [134]). On the other hand, $CT_i = 0$ allows for microgrid export, as long as the lower operating limit for the smallest FG unit is not reached [135].

The intended RE installed capacity is likely to encounter limits set by the utility to avoid any negative impacts on voltage and reactive power in the existing microgrid system [136]. In the Northwest Territories, for example, the RE installed capacity restriction has been set as a percentage of the RC annual average load [137]. Hence, this constraint is modelled as:

$$\sum_{i=1}^I \sum_{k=1}^K RP_k EOS_{i,k,t} \leq b_{IC_t}^{\max} \frac{\sum_{h=1}^H P_{D_t,h}}{H} \quad (5.36)$$

where $b_{IC_t}^{\max}$ is the maximum RE installed capacity ratio.

This planning model deals indirectly with the technical aspects of the RE equipment placement problem by considering the economic and technical considerations previously described. In the case of system losses, the model will tend to install more RE equipment for SC projects where the AERs are the highest, as per with (5.11). Furthermore, the microgrid stability issue is somewhat considered in the model using (5.36), since this constraint is expected to be set by the utility.

The economic feasibility of the planning scenario is given by the combined result of the NPV and the IRR. In the model, NPV is directly accounted for as part of the social welfare objective function (5.9). However, maximizing $W_{i,t}$ does not necessarily mean that the project is financially attractive, since the project's resulting IRR must be above the pre-defined discount rate to be appealing to the involved stakeholders. Hence, the following constraints are included in the model:

$$\sum_{t=1}^T \frac{W_{i,t}}{(1 + IRR_i)^t} = 0 \quad \forall \quad \sum_{k=1}^K \sum_{t=1}^T x_{i,k,t} \geq 1 \quad (5.37)$$

$$IRR_i^{\min} \leq IRR_i \leq IRR_i^{\max} \quad (5.38)$$

where the parameter IRR_i^{\min} defines the minimum IRR required to make the project financially feasible, and the upper limit IRR_i^{\max} is only used when an incentive program is considered, i.e., when the model is used to determine an economically viable incentive for all stakeholders.

RE projects for the same equipment type and customers are likely to be funded and deployed only once over the planning horizon. This consideration avoids repeating project activities in different planning years, such as equipment transportation for the same project over two different years or decommissioning. This constraint is implemented by:

$$x_{i,k,t} = EOS_{i,k,t} \quad \forall \quad x_{i,k,t} > 0 \quad (5.39)$$

5.3 Case Study: Kasabonika Lake First Nation

The case study aims to apply the model to create a multiple-year RE plan for the KLFN community described in detail in Section 4.3.

As for the RE equipment the model includes the following equipment components. The solar PV panels considered are: 230 W_p Kyocera, 220 W_p Sanyo, and 230W_p and 240W_p Canadian Solar modules. The solar inverters are: 6.3 kW SMA, 10 kW Fronius, 10 kW Mastervolt, and 10 kW Aurora/PowerOne. The WT units are: 50 kW Endurance; 60 kW, 95 kW, and (2×) 100 kW Northern Power; 30 kW Wenvor; and 10 kW Bergey. These pieces of equipment were selected since they are commercially available in Canada and can potentially be transported to the community (e.g., via winter roads).

The objective of the case study is to determine the most feasible RE alternatives over a 20-year planning horizon, considering a project investment period of 5 years. The operation schemes are: SC for the community-owned buildings (i.e., school and water treatment plant), where load data is available, and AFC for the rest of the load. Table 5.2 presents the parameters fixed for all scenarios in the studies, which were obtained from KLFN, HORCI, and historical estimates. Note that in the case of KLFN, there is currently no RE generation incentive ($INC_i=0$), and the utility purchases directly diesel fuel for electricity generation; hence, there is no loss of opportunity cost for the community with regards to fuel sales ($LR_{i,t}=0$). In addition, the model assumes that project investments take place at the start of each year, while their operation does not start until middle of the year.

The planning model was implemented in MATLAB and a GA from the Global Optimization Toolbox was used to solve the MINLP problem for Stage IV in Figure 5.1. GA was selected as the optimization algorithm for the following reasons:

- *Previous use of GA in microgrid planning problems:* As described in Section 2.3, GAs have been successfully used in microgrid planning problems due to their flexibility to deal with objective functions and constraints without requiring associated derivatives, which in some instances might not be feasible to compute due to discontinuities in the respective functions.
- *MINLP problem solving:* The nature of the RE planning model requires handling integer variables and non-linear constraints, which require special solvers that present several challenges as the size of the problem increases. These types of problems can be readily solved using GA, when computational times are not an issue.
- *Off-line programming:* GAs are heuristic optimization tools that create a population of candidate solutions across the variables search space; depending on the number of variables, such process can be computationally intensive and not appropriate for solving problems in real-time. However, the RE capacity problem is a long-term problem that can be solved off-line; hence, GAs are an adequate tool for solving this RE planning problem.

For the proposed RE planning problem, the GA used considers an initial population of 15 times the number of system integer variables $x_{i,k,t}$; a crossover fraction of 0.97; a convergence tolerance of 1e-08; and a 3 generation stall limit. For the selected case studies, the average computational time for the scenarios analyzed was 15 minutes using an Intel Core i5 processor at 2.5 GHz.

5.3.1 Scenarios

The following scenarios are based on some of the alternatives and parameters of concern while planning RE project(s) in RCs:

- *Funding alternatives (b_{CEP} and b_{EFP}):* Scenario 1 considers the baseline where one stakeholder funds the total projects' cost. Scenario 2 incorporates a loan alternative

Table 5.2: RE planning model parameters for the KLFN case study

Param.	Value	Param.	Value
b_{CB}^{\max} (%)	20	d_{GS}^{\min} (%)	40
b_{CBu}	20	$d_{GSLIM_{i,t}}$ (%)	40
b_{CFP_t} (%)	0	ELT_k (years)	15
b_{EFP} (%)	50	INC_i (\$/kWh)	0
b_{OM_t} (%)	0	IRR_i^{\min} (%)	8
BLT_k (years)	15	r_{FR} (%)	10
CD_i (\$/kWh)	0.926 ^a 0.394 ^b	RC_{CAP_k} \$/W	9 ^c 12 ^d
C_{FUEL} (\$/litre)	1.85	RP_t^{\min} (kW)	400 ^e 600 ^f

^a Unsubsidized electricity rate. ^c Solar PV cost, ^d WT cost.
^b Avoided fuel cost rate. ^{e,f} Before and after the 400 kW FG is decommissioned.

to finance the projects, since initial economic resources are likely to be limited. Scenarios 3-12 considers the loan alternative plus external government funding aimed to promote northern development available for community-driven projects.

- *Discount rate (RD)*: Scenario 3 considers the social discount rate of 4% used by the Ontario Power Authority (OPA) for project assessment. Scenarios 4 and 5 consider higher discount rates 6% and 8%, respectively, to assess the higher risk or uncertainty of future cash-flows. For the rest of the scenarios, a discount rate of 6% was used.
- *Fuel cost growth (CPI)*: Scenario 6 considers a 5% annual growth rate for the diesel-fuel cost which is equal to the average of the 10-year compound growth rate for fuel prices in northern Ontario since 2000. Scenario 7 considers a higher rate, 7% fuel cost growth, and all other scenarios use a 4.5% annual growth, the average of 5-year compound growth rate.
- *RE capacity limit ($b_{IC_t}^{max}$)*: Scenario 8 eliminates the installed capacity constraint described in (5.36). For all other scenarios, the RE installed capacity limit is set to 50% of the annual average community load, since by trial-and-error, the model does not yield higher RE outputs for larger values, i.e., it does not make economic sense to have higher RE penetration levels. Note that in the Northwest Territories, this limit is set to 20% by the current policy; however, this yields very low RE penetration levels in this case study.

- *Solar irradiation*: Scenarios 9 and 10 represent the respective lower and upper expected variation limits for the annual average solar global irradiation. Based on the correlation data available for a location of similar latitude, the variation considered is approximately $\pm 6\%$. For the rest of the scenarios, an annual average solar irradiation of $2.9 \text{ kWh/m}^2/\text{day}$ is assumed.
- *Wind speed*: Scenarios 11 and 12 analyze the effect of lower and higher wind speeds, $\pm 10\%$ of the annual average wind speed; however, based on the correlation information and performance of the currently installed WTs, the actual value is closer to the lower bound [108]. The rest of the scenarios are based on an annual average wind speed of 5.61 m/s .

The aforementioned parameter values for the different Scenarios are shown in Table 5.3.

Table 5.3: KLFN case study parameter values.

Scenarios	Parameters						
	b_{CEP} %	b_{EFP} %	RD %	CPI %	$b_{IC_t}^{\max}$ %	Annual average	
						G $\text{kWh/m}^2/\text{day}$	ws m/s
1	100	0	6	4.5	50	2.90	5.60
2	10	0	6	4.5	50	2.90	5.60
3	10	50	4	4.5	50	2.90	5.60
4	10	50	6	4.5	50	2.90	5.60
5	10	50	8	4.5	50	2.90	5.60
6	10	50	6	5.0	50	2.90	5.60
7	10	50	6	7.0	50	2.90	5.60
8	10	50	6	4.5	-	2.90	5.60
9	10	50	6	4.5	50	2.73	5.60
10	10	50	6	4.5	50	3.02	5.60
11	10	50	6	4.5	50	2.90	5.07
12	10	50	6	4.5	50	2.90	6.19

5.3.2 Results

Each scenario gives a multiple-year RE plan for the community. A detailed explanation of Scenario 3 that encompasses all the available options of the model is first presented, followed

by a general discussion of all twelve selected scenarios. The solution to all scenarios was obtained using a desktop computer with a 2.5 GHz Intel Core i5 CPU, and took an average of approximately 15 min. for each scenario.

5.3.2.1 Scenario 3

This is the first scenario that considers the diverse funding mechanisms which are likely to be available for community-driven RE projects. Hence, this scenario shows the capabilities of the proposed model, which yields multiple RE equipment deployments over the planning horizon. Figure 5.4 (a) shows the solar PV cost reduction over the years resulting from the CB process considered by the model, as per (5.15), which intrinsically promotes further solar PV deployment. Figure 5.4 (b) presents the proposed installed capacity for each type of project and operation scheme; in this case, both SC and AFC schemes are economically feasible, and since the loads for the water treatment plant and the school are known, the capacities at such locations can also be identified. The total planned RE capacity is 260 kW, which corresponds to approximately 47% of the annual average load (the maximum RE installed capacity limit was set to 50%).

Figure 5.5 presents the power supplied per type of generation unit for 3 sample days; the FG units switch accordingly to satisfy high- and low-load requirements, as expected, where RE can be considered a negative load due to the low penetration level, having a maximum RE penetration in one hour of 35% (power), and the highest annual RE contribution of 7% (energy) over the planning horizon.

Figure 5.6 shows the components of the annual social welfare W over the planning horizon. First, the combination of the external funding and the loan alternatives assure that the initial cash contribution from the community remains low, so that RE projects do not compete with other priority projects within the community. Second, the RE projects bring a direct benefit to the community, since they will be the equipment owners; such benefit comes with the responsibility of covering the loan payment schedule. The intention of the loan is not only to obtain financial feasibility, but also to become a commitment for the stakeholders to maintain the equipment in operation, as well as to afford the relatively high on-site O&M costs, which in this case corresponds to approximately \$0.09/kWh and \$0.15/kWh for the solar PV and WT equipment, respectively.

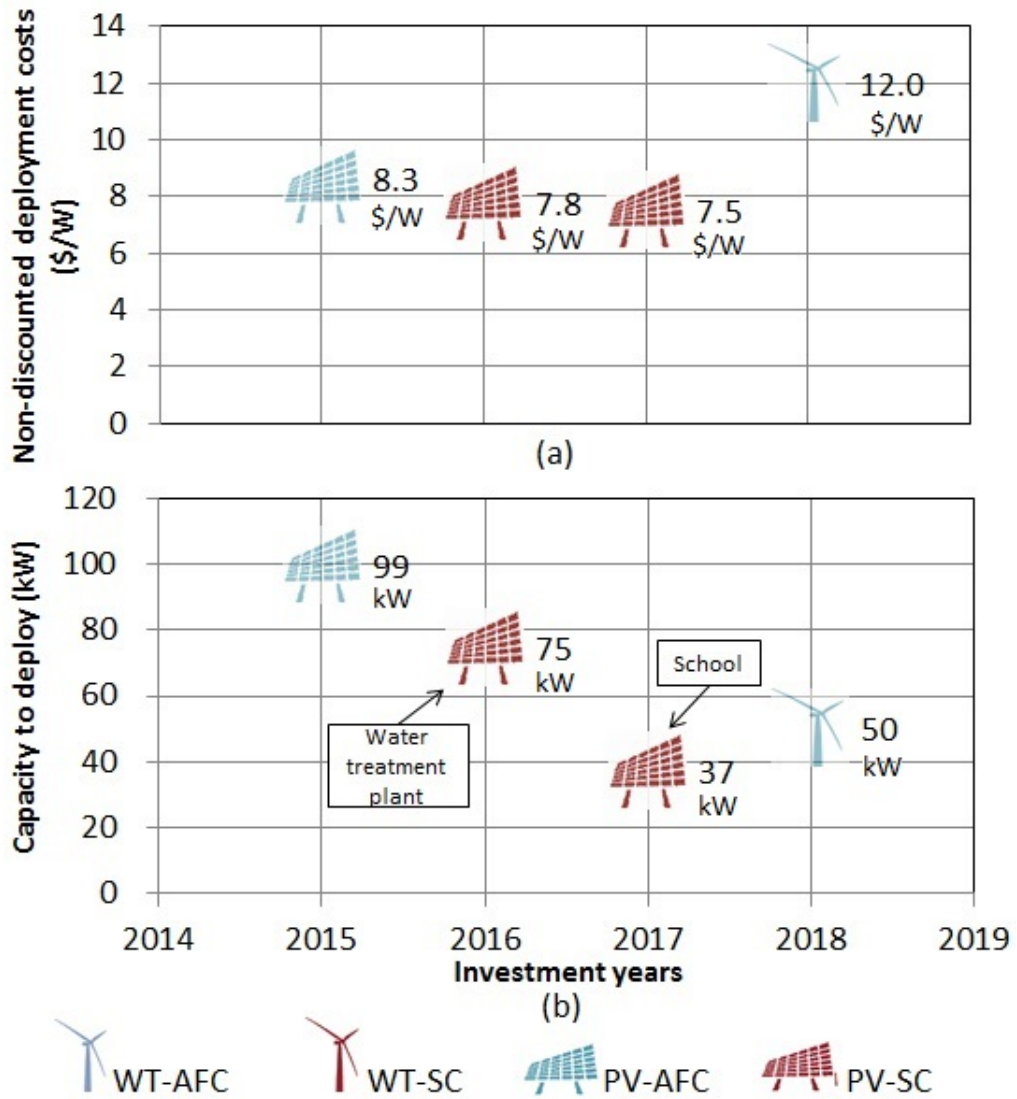


Figure 5.4: Scenario 3. RE long-term plan: (a) deployment costs and (b) capacity.

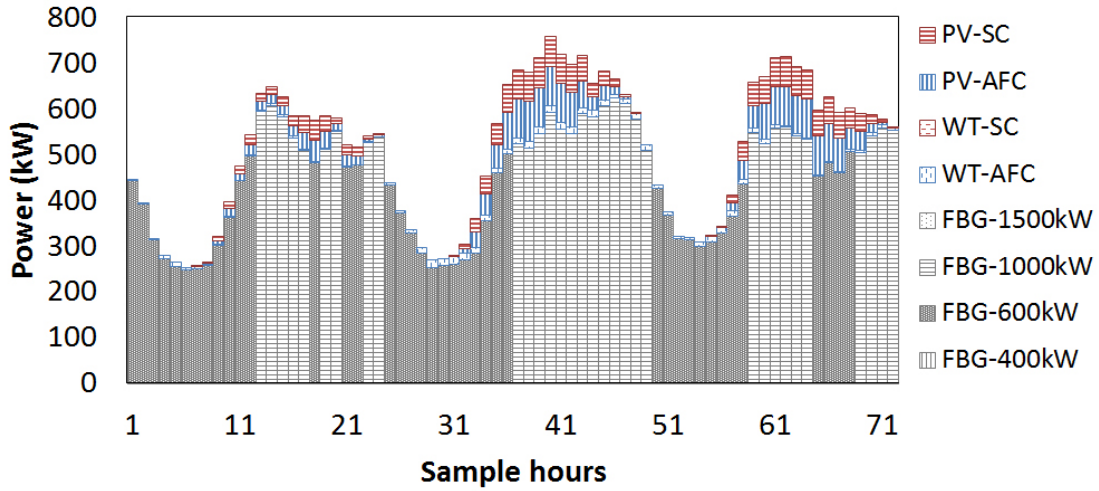


Figure 5.5: Power output per generator type for Scenario 3 after all RE equipment has been deployed (June 23-25, 2020).

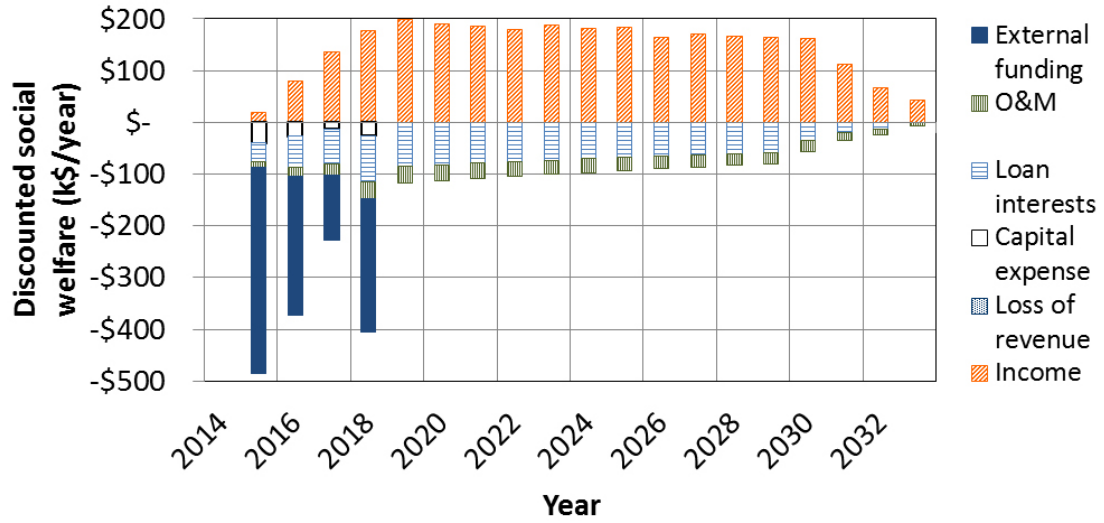


Figure 5.6: Cash-flow for Scenario 3.

5.3.2.2 All Scenarios

Generation

Figure 5.7 shows the proposed RE deployed capacity by technology and operating scheme for each scenario. Scenarios 1 and 2 are the most limited cases with 100 kW of installed capacity, since the investments are not distributed among different funding alternatives, and as a result only PV-SC projects are marginally feasible. Scenarios 3 to 12 consider external funding, thus reducing the community project expenses, and resulting in higher feasible RE deployment capacities. For these scenarios, the selection of the discount rate value has the highest effect in the RE capacity output. Hence, the social discount rate of 4% allows for 274 kW of RE deployment, while the more conservative 8% discount rate only allows for 236 kW; this reduction is mainly seen in the AFC operating scheme. Scenarios 6 and 7 show that changing the compound annual fuel growth rate from 5% to 7% results in an installed capacity difference of only 12 kW; the reason for their relatively minor change is that the current subsidy framework reduces the direct effect of fuel price in the electricity rate. Scenario 8 proposes RE projects of 300 kW capacity when no pre-defined installed capacity limit is set, which corresponds to $b_{IC_t}^{\max} = 54\%$; hence, there is no further economic benefit of increasing RE capacity beyond this level under current operating conditions. Scenarios 9 and 10 show that even with the potential solar irradiation variation, the expected RE installed capacity is maintained at 274 kW, which highlights the use of solar technologies in such location. Finally, Scenarios 11 and 12 show that WT technology is not feasible when considering the expected variation in annual wind speed; if the actual wind speed decreases by 10%, WT technology is not included in the deployment plan.

Figure 5.8 shows the annual RE generation for the selected scenarios, which is evidently proportional to the respective installed capacities just described above. The annual RE contribution for the analyzed scenarios is below 6% of the total annual load which is a modest contribution. However, for example, for Scenario 8 it saves approximately 90,000 litres of fuel per year, as well as creates an economic benefit for the community as discussed in the next section. Additionally, the RE curtailed for all scenarios is very low; for example, Scenario 8, it corresponds to 3.2% of the total RE generation, which is equivalent to a loss of approximately \$6,000 per year.

Figure 5.9 presents the maximum RE penetration in one hour, which is the time resolution of the proposed model. Observe that, even in the case of no RE penetration limit

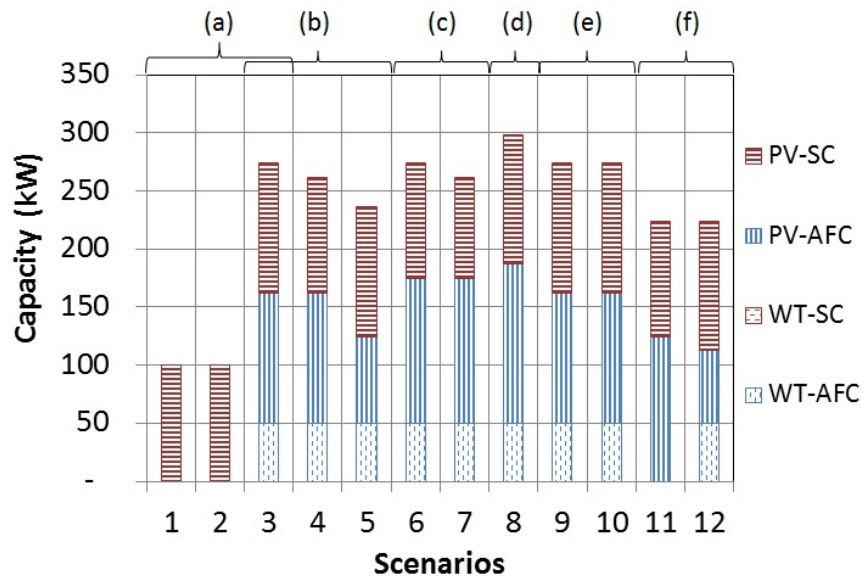


Figure 5.7: Proposed RE deployment capacity per scenario: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.

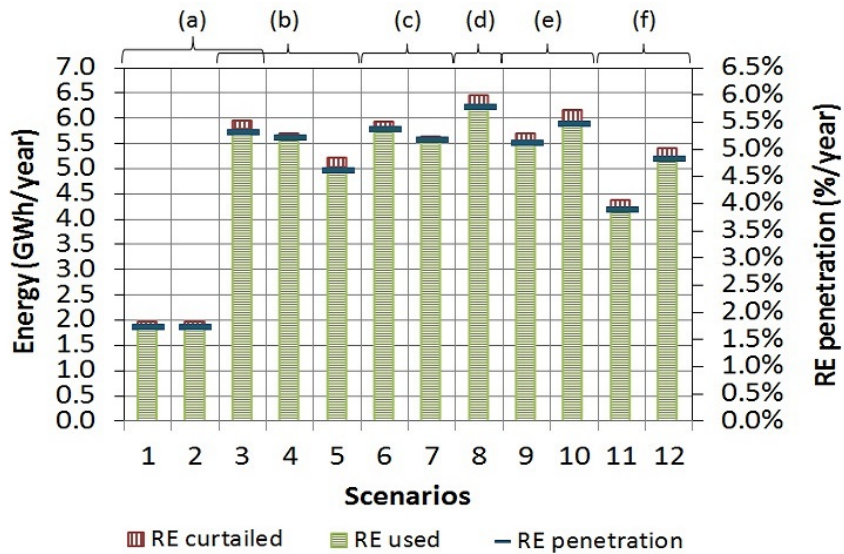


Figure 5.8: Proposed annual RE contribution: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.

(Scenario 8), it does not exceed 46%, i.e., at no point the total community load is fully supplied by RE. It should be mentioned also that the model assumes that FGs are always on-line, and thus at least 15% power reserve is provided as backup for RE in case of intermittent wind or solar variations.

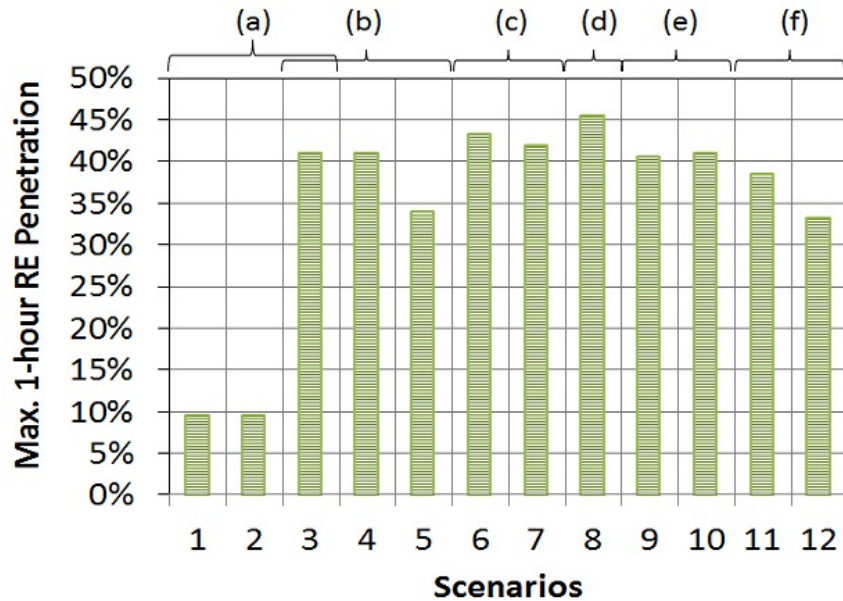


Figure 5.9: Proposed maximum RE penetration in one hour: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.

Economics

Figure 5.10 presents the net present value of the social welfare and its breakdown for each of the selected scenarios. Scenario 1 and 2 show a relatively low social welfare of \$205,000 and \$158,000, respectively, when compared to the remaining scenarios, which results in significant investment risks given the low economic return and high capital costs, and is similar to the results obtained in Chapter 4, which make these scenarios marginally feasible. Furthermore, Scenario 1 requires a large capital expense at year 1; and the bank loan in Scenario 2 presents high loan interests with regards to the income. Scenarios 3 to 12 present different present value breakdowns and a higher social welfare due to provincial/federal funding for the projects. The social welfare for these scenarios range from \$1.6 million to \$2.3 million, given that external funding does not create any loan interests while reducing the capital expenses for the community. Additionally, these capital expenses are further

reduced, given the bank loan where the payments become the highest expense and an incentive to maintain the system in operation. Finally, the O&M costs are on average 15% of the generated income.

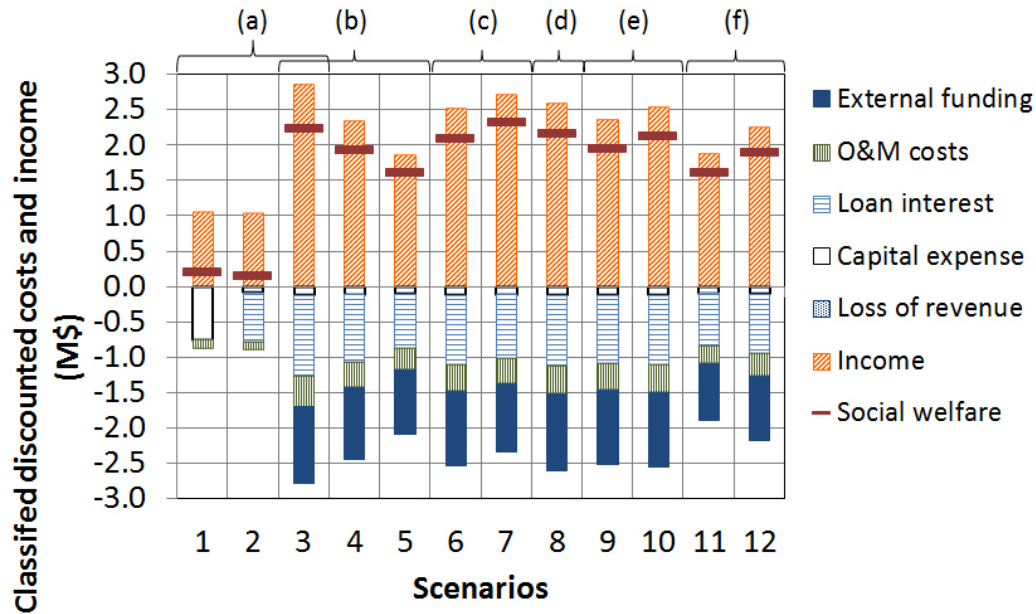


Figure 5.10: Discounted social welfare breakdown: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.

Figure 5.11 presents the IRR per type of project and scenario. Scenarios 1 and 2 have a relatively low IRR, and as a result are not attractive alternatives. Scenarios 3 to 12 have significantly higher IRR due to the risk and expenses being shared among stakeholders. For all scenarios, the community IRR increases for both SC and AFC projects, since from the community perspective, the capital expenses are reduced by 50%, while still obtaining the total benefit from the proposed projects. This figure also shows the IRR obtained from the external funding received when considering that government fuel subsidies are reduced. In Ontario, approximately 66% of the total fuel cost in HORCI operated communities comes from a provincial government subsidy; hence, if RE generation reduces fuel consumption, the total subsidy contribution from the government will also be modestly reduced. Thus, from a policy perspective, supporting such remote RE projects would also benefit the government on top of other social benefits.

Government agencies are the anticipated source of external funding for RE projects [132–

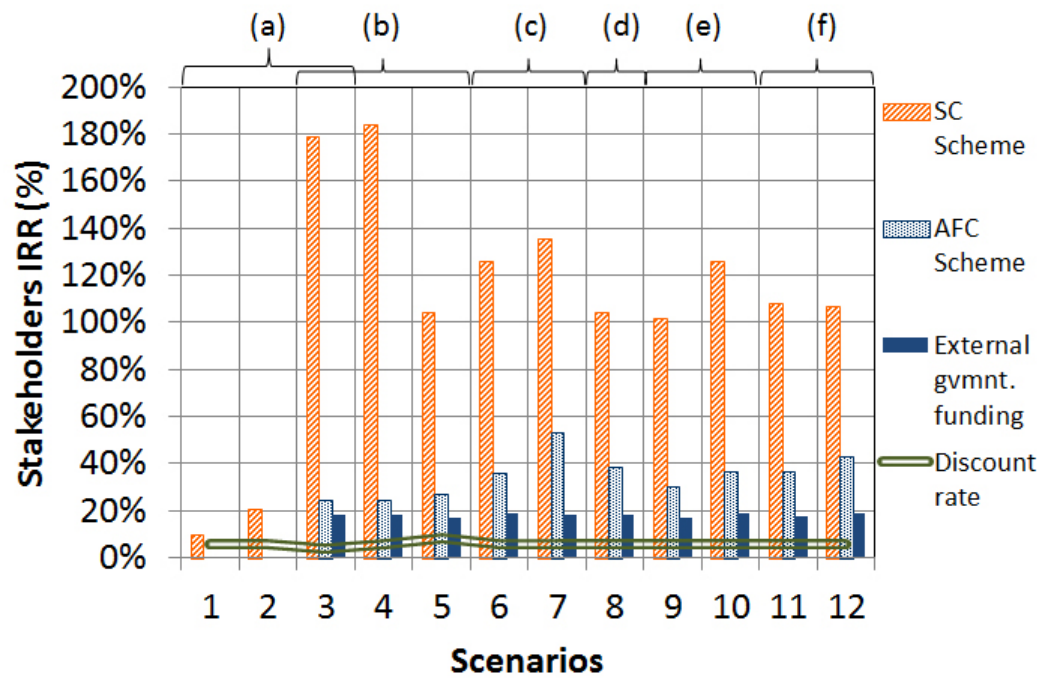


Figure 5.11: IRR obtained per stakeholder and scenario: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.

134], and indirectly would benefit from such projects. One of the main benefits of such projects is the support of economic development activities for RCs; however, there is an indirect economic benefit for these agencies. As described in Chapter 3, the provincial and federal government subsidize the electricity operation in RCs; hence, reduction in fuel consumption would decrease the amount of subsidy required for the operation. Figure 5.12 makes a comparison between the amount of external funding awarded for RE projects and the obtained subsidy offset that the fuel reduction generates over the projects' lifetime. For Scenario 3 to 12, the government not only recovers the project investment, but would also accrue savings due to the reduction of diesel fuel over the lifetime of the project.

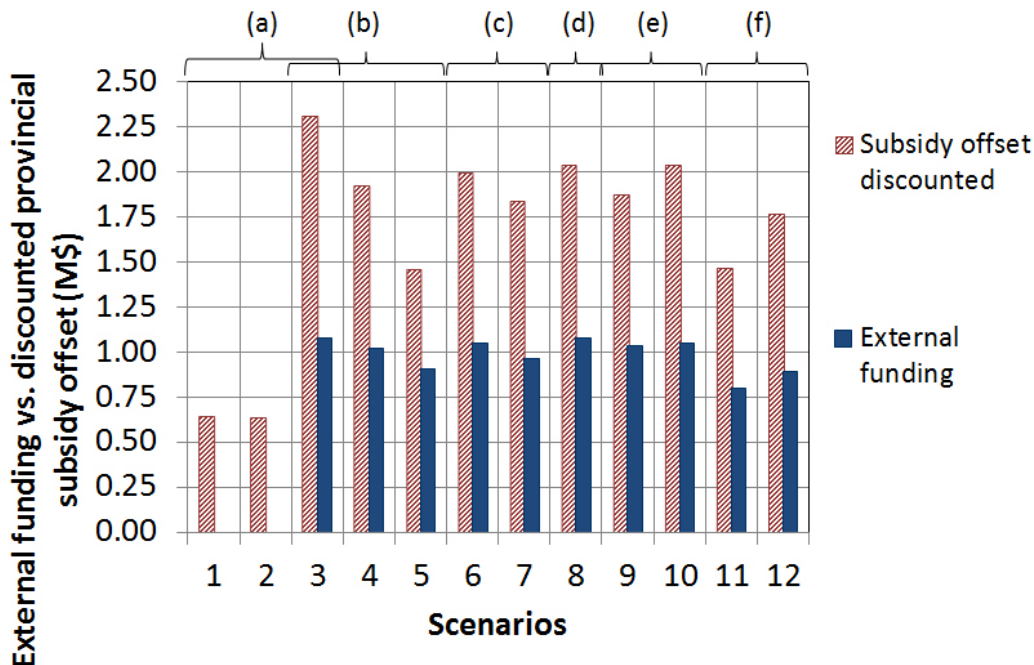


Figure 5.12: External funding versus subsidy offset: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, and (f) wind speed levels.

5.4 Summary

A novel LTRGP model for RCs has been presented in this chapter. The chapter first describes the relationship between the current AERs and the potential operating frameworks

in which RE can be installed in RCs. Next, the mathematical model was discussed, considering the constraints imposed by the available input information and the community characteristics. Finally, a relevant case study based on KLFN was presented, considering a series to analyze the impacts of the model parameters.

The results demonstrate that realistic RE community plans can be obtained with the proposed model, considering wind and solar equipment that have or can be deployed and operated in such remote locations, while producing a direct economic benefit to the community and indirectly to the government agencies that support such projects. The model should be applicable to RCs in jurisdictions with characteristics similar to those of Canadian RCs, such as in Alaska and Chile.

The content of this chapter has been submitted for publication [\[138\]](#).

Chapter 6

Summary and Future Work

6.1 Summary and Conclusions

Chapter 2 presented a brief overview of microgrids and their advantages and challenges. Particularly, the current dispatch strategies for diesel-based microgrids were presented, highlighting the characteristics of the simple, yet robust, single and parallel dispatch strategies. Furthermore, the RE equipment mathematical models, which were used in the remaining chapters of this thesis, were discussed giving special attention to the temperature effect issue in northern locations. The advantages and current restrictions of available RE microgrids planning tools were also presented, highlighting the need for a long-term planning model for RCs considering relevant constraints. Finally, an introduction to MINLP problem was given, and some of the available solution techniques for this type of optimization problem were described, of which GA was used in this thesis, as background for the formulation of the LTRGP problem discussed in Chapter 5.

Chapter 3 presented a general overview of different technical, economic, social, policy, and environmental issues that needed to be considered to properly understand the electric energy situation in N&RCs. A summary of the solar and wind resources obtained as part of this research was also presented, including some of the related maps produced in the course of study, and discussing the benefits and limitations of using the available time-series data to propose RE projects in Canada's remote locations. The main objective of this chapter was to provide a better understanding of the challenges and opportunities with regard to electricity generation in Canada's N&RCs. There is significant RE potential in N&RCs; however, more than half of the people in these communities still rely solely on

fuel-based sources for electricity generation, mainly due to the communities' geographical locations and low population densities. Recent RE studies and projects have aimed at slowly changing the perception that diesel fuel is the sole alternative for such communities; however, there are still significant challenges involved in changing the existing energy mix to include significant contributions from RE sources.

Chapter 4 discussed and presented a methodology to evaluate the possible integration of RE technologies in Ontario's RCs. A customized analysis of RE equipment and deployment costs was also presented to evaluate RE projects in remote locations, using the KLFN community as a reference. Six case studies were presented for this community, analyzing the economic feasibility of three low-RE-penetration scenarios (7%–9%) and three medium-RE-penetration scenarios (18%). It was shown that the RE installation cost can be as high as 2.5 times that of an equivalent on-grid system. Furthermore, given the current deployment conditions, it was concluded that RE deployment in the KLFN community was not economically feasible, given the high capital investments required. However, as it was discussed in the Chapter 5, more accurate modelling and alternative funding considerations for the RE deployment problem can result in feasible alternatives for the community.

Chapter 5 presented a novel LTRGP model for RCs. The chapter first described the relationship between the current AERs and the potential operating frameworks in which RE can be installed in RCs. Next, the mathematical model was discussed, considering the constraints imposed by the available input information and the community characteristics. Finally, a relevant case study based on KLFN was presented, considering a series to analyze the impacts of the model parameters. The results demonstrate that realistic RE community plans can be obtained with the proposed model, considering wind and solar equipment that can be deployed and operated in such remote locations, while producing a direct economic benefit to the community and indirectly to the government agencies that support such projects. The model should be applicable to RCs in jurisdictions with characteristics similar to those of Canadian RCs, such as in Alaska and Chile.

6.2 Main Contributions

This thesis identifies and analyzes in detail the electrical energy challenges in N&RCs, and proposes LTRGP models that can be implemented in these communities, considering current technical and economic conditions. The main contributions of this research are:

- Create a detailed database of Canada’s N&RCs to assess the energy-related opportunities and challenges in these northern locations. The database helped shape the proposed RE planning models since they were based on the information obtained from the communities, hence making the models more accurate, relevant, and realistic. Furthermore, this database has been used as an important source of information by other researchers working in N&RCs microgrids.
- Develop a multi-year RE planning model that can help RCs determine the feasibility of energy projects, considering the characteristics of remote microgrids. The intention of these models is to provide feasible economic RE alternatives by sharing the economic risk among stakeholders, while considering deployment and operating constraints in RCs.
- Creating relevant case studies based on up-to-date information available due to the close collaboration with KLFN. The intention of the case studies is to provide the KLFN community with an RE plan that could be implemented under the current economic and technical conditions.

The findings of Chapter 3 have been published in the IEEE Power and Energy Magazine [94]. The methodology and results of Chapter 4 have been published in the IEEE Transactions in Sustainable Energy [104]. Finally, the RE planning model presented in Chapter 5 has been submitted to the IEEE Transactions in Sustainable Energy [138].

6.3 Future Work

The following future research topics could be considered to improve the proposed LTRGP model:

- Enhance the proposed model to better account for operational constraints, as well as environmental and social issues.
- Extend the scope of the planning model to other RE sources and remaining energy services, such as community heating requirements. The intention of this future work is to create models to develop comprehensive energy strategies for communities.
- Analyze and propose external RE incentives that can properly promote RE technologies in N&RCs.

- Consider higher resolution data (e.g., sub-hourly measurements) for sample intervals to assess the technical feasibility of systems where higher RE penetration levels are desired.

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