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A Robust Planning Model of Sustainable Energy for Remote Communities

Rajesh.K[1] and Jaya.N[2]

[1]Department of Electrical and Electronics Engineering

[2]Department of Petrochemical Technology, Bharathidasan Institute of Technology Campus, Anna University, Tiruchirappalli, Tamil Nadu, India.

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ABSTRACT

This paper presents a novel long-term renewable energy (RE) planning model for remote communities (RCs). Over the past few years, there has been a significant increase in assessing and deploying RE projects in northern remote locations. The model proposed in this paper adds to such efforts by creating a multiple-year community planning tool. This can be used to determine economic and technically feasible RE solutions, considering the current operating structures, electricity pricing systems, subsidy frameworks, and project funding alternatives under which RE can be deployed in RCs. The proposed model is implemented in a case study. The case study shows that RE projects can be feasible undercurrent operating conditions, for a set of funding alternatives that share the economic risks.

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Introduction

High energy costs, together with technical, environmental, and social aspects, have gradually triggered RE assessments, projects, and policies in remote communities (RCs). In particular, previous and ongoing projects have been paving the way for further RE development in Canada's northern locations from the Yukon to Newfoundland with recent efforts to increase the access to energy-related information from RCs to promote further developments also, there has been escalating efforts to assess appropriate equipment, natural resources, and economic feasibility of such projects [1]. While pointing out the potential of RE projects, these efforts highlight the shortcomings as well as the technical and economic barriers that are yet to be over-come , which include electric energy storage systems that, for medium or high RE penetration levels, are yet to significantly decrease the overall cost of energy under current deployment conditions . Furthermore, to properly evaluate the technical and economic RE aspects of such projects, from a planning perspective, there are still limited tools that consider the specific challenges of RCs; this is the focus of this paper.

There has been significant work regarding RE micro grid planning and sizing considering different model detail levels, objective function(s), and equipment characteristics Detailed dynamic models have been proposed to assess feasibility of RE configurations based on energy availability and equipment downtime thus resulting in technically feasible solutions, but not necessarily economically viable [2]. Further deterministic models have been used for economic evaluations considering tradeoffs between reliability and cost as well as proposing multi objective interval linear programming (ILP) to assess risk levels for different configuration These previous approaches consider significant levels of detail while accounting in some cases for some of the uncertain-ties that result from micro grid sizing; however, the long-term role of the associated community and funding details have not been considered [3]. In the latter, investment opportunities have been analyzed for grid-connected micro grid models dealing with investment periods and uncertainties some of these concepts can be translated to RCs, as shown in this paper.

Micro grid sizing software considering different approaches are available. Thus, HOMER is a widely used software for micro grid sizing that determines the minimum configuration; however, the software considers individual projects with the same operating structure, which can be a limiting factor when creating an RE plan for a community [4]. Also, a comprehensive economic and environmental model that can be used for determining the minimum cost equipment configuration for a micro grid however, multiple-year investment and project funding alternatives are not considered. These shortcomings are addressed in this paper.

Previous projects, assessments, planning models, and soft-ware tools have helped understand the complexity and requirements of deploying RE in RC micro grids. Nevertheless, currently, there is a gap from the planning perspective to help communities understand and quantify the potential of RE and the benefits that RE projects can bring, given the current operating and framework constraints [5]. Hence, the objective of this paper is to use existing equipment and economic models to propose a comprehensive RE long-term planning model that accounts for all relevant and current technical, economical, and operating conditions of RCs. The proposed model considers the characteristics of some of the previously deployed RE northern projects and previously described planning models which apply directly to RCs. In addition, the model acknowledges some of the significant roles that the community plays regarding potential RE project deployments, as well as quantifying the project benefits .This paper is organized as follows.

Tele: +91-9790372124

E-mail address: rajeshme95@gmail.com

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Section II discusses the different electricity rates and subsidy framework in northern and remote communities (N&RCs) in Canada, and their relation with RE project operation schemes, which are relevant to the proposed planning model [6]. Section III presents the proposed mathematical model for long-term RE planning. Section IV presents the case study developed in collaboration with Kasabonika Lake First Nation (KLFN), and discusses the results of applying the proposed model to develop a multiple-year RE plan considering multiple scenarios. Finally, Section V highlights the main conclusion and contributions.

Electricity Rates and Subsidies

Community applicable electricity rates need to be understood to assess the potential benefit of RE projects in RCs. In Canada, electricity rates 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 [7]. The details and subsidy levels differ by location; however, a generalized rate classification can be as follows:

1.Unsubsidized Customer: 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 and have installed RE equipment for self-consumption (SC) purposes.

2.Subsidized Customer: 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.

3. Alternate 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 ultimately represents the energy cost that RE projects compete against [8,9]. The rate is approximately 40 % to 60 % of the energy cost depending on the RC location. A power purchase agreement (PPA) can be established with the utility to export RE power to the micro grid, fixing the rate to the AFC.

Planning Mathematical Model

The main objective of this paper is to develop a multiple-year RE planning model that can help RCs determine the feasibility of energy projects considering the characteristics of remote micro grids. The model maximizes the potential benefit or social welfare perceived by the community while identifying:

- RE equipment type and capacity to be deployed.
- Operation schemes under which RE units can operate.
- Installation time-frame for RE equipment and its location for customers whose current load demand is known.

1. Model Architecture

Fig. 1 shows the structure of the proposed model, which is composed of four stages. The input data stage includes historical data for natural resources, community location and energy related information, and FG and RE equipment specifications. The forecast stage creates the time-series estimates for the electric load, and the onsite RE resources for the planning horizon [10]. The preprocessing stage calculates the dispatch strategy details for FGs, estimates the power profile, and pre-selects configuration details for each RE equipment type and overall generation costs. Finally, the optimization stage solves a proposed Mixed Integer Nonlinear Programming (MINLP) problem that maximizes the RE planning social welfare for the community.

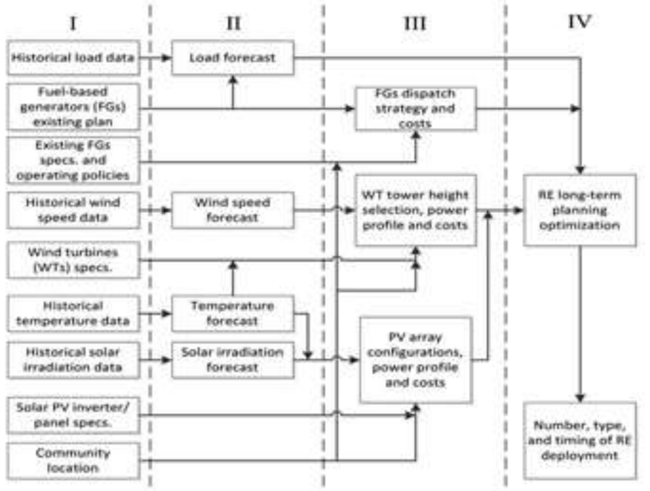

Figure 1. Mathematical model architecture.

It is important to note that, based on battery energy storage is not considered as a viable alternative in the proposed model. Under the current conditions, battery energy storage for RCs presents several challenges such as thermal management and investment and O&M costs that do not make it a feasible option in the medium term.

2. Load and Installed Equipment: Detailed historical information for the majority of RCs is available from off-grid utilities, once a community grants access to such information. The minimum data requirements for this model are the hourly load time series and the annual electricity demand growth rate. In some cases, seasonal growth rates are preferred due to the wide load level range throughout the year. In addition, electricity consumption for large individual customers might be available for the RE planning model.

3. Solar-Related Resources: Solar irradiation data are widely available in the literature with different levels of resolution. However, there are significant drawbacks when considering remote northern locations. Hourly solar irradiation is easily available only for sites south of latitude 58 °N. In Canada, such northern sites account for approximately 100 communities and 1,00,000 people, covering one-third of the total N&RCs. In addition, there is limited correlation between satellite and ground data for northern latitudes, which decreases the accuracy of the available data by approximately 10 % to 15 %. Temperature data are usually available from the same sources.

4. Wind Resource Data: Low-resolution wind speed data can be easily obtained from different sources; however, these data are usually limited to seasonal or annual averages. Onsite wind speed data are seldom available for RCs; thus, synthetic mesoscale data are the next alternative data source. As with the solar resource, wind speed has the aforementioned correlation issue between ground and modeled data. The limited available studies give a significant wind speed range for northern locations, in most cases, greater than ±0.5 m/s annual average, which, for some locations, represents a ±10% difference. An additional alternative in remote locations is to obtain wind speed data from the local airport to validate mesoscale estimations; however, some remote airports do not store wind speed data and hence historical logs may not be available, as in the case of most of the communities in Northern Ontario, Canada.

Forecasts

1. Electric Load Forecast: A historical multiple-year hourly data can be used to create a load forecast that follows the

current load profile in the community. In this paper, a normal distribution function is used to perturb the existing data, based on historical annual growth rates; in some locations, seasonal growth rates can be used to more accurately represent the growth variation within a year. In addition to the historical growth, the current electric generation installed capacity in the community needs to be considered to create the forecast.

2. Solar Irradiation and Temperature Forecasts: Likewise to the electric load forecast, the solar and temperature forecasts are obtained by perturbing the historical hourly data by assuming a normal distribution of the annual average value for the respective parameters [11-13]. In most cases, available data expand for 10 years or more; hence, a representative data sample can be used to create these forecasts.

3. Wind Speed Forecast: This forecast can evidently 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, as described. Such methodology is followed here to create the forecast assuming a normal distribution for the annual wind speed averages.

Generation Equipment Considerations

The proposed long-term planning model requires electricity generation equipment calculations that precede the optimization step. The calculations include the dispatch strategy details for FGs and onsite available power, and for the RE equipment under consideration, as described in the following sections.

1. Fuel based Generator (FG): The unit commitment and economic dispatch problem for FG facilities in RCs is trivial when compared to an on grid system, simply because of the limited installed capacity and consequently less operating alternative. The dispatch strategy is determined by the operating limits in the plant programmable logic controller (PLC), which simultaneously deals with the spinning reserve and the economic unit commitment problem. The PLC limits and set points keep approximately a 15 % spinning reserve margin, as well as committing units with the minimum marginal cost, under normal operating conditions.

2. Solar PV: 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 to identify the best PV array configuration for each module type and, at the same time, to reduce the search space for the optimization process. Such preselection is done by estimating the solar PV array total cost.

3. Wind Turbine: The WT preselection process determines the most cost-effective WT/tower height set selection for each unit type, as well as the corresponding power output profiles. The process calculates the wind speeds at the different heights and determines the total deployment costs, thus reducing, as with solar PV preselection, the search space during the optimization process.

RE Long-Term Planning

1. Objective Function: The long-term planning model is an MINLP problem that maximizes the benefit to the RC, given the deployment and operational constraints of such locations.

2. Financial Indicators: The proposed model uses various financial indices at different stages to quantify the economic feasibility of the proposed projects. The main index of the social welfare in which the model aims to maximize, so that the community benefits best from RE deployment projects. However, on its own, the social welfare does not assure that the proposed projects are financially attractive, since the resulting may not cover the operating and financial expenses over the project lifetime. Furthermore, the proposed model considers RE equipment that produces the highest cost / benefit return through the minimization of each type of technology under consideration, as per. Overall, the intention of the financial indices is to obtain not only technically but financially feasible scenarios that can be currently implemented in RCs.

Case Study: Kasabonika Lake First Nation (KLFN)

The case study aims to apply the model to create a multiple-year RE plan for KLFN, an Oji-Cree First Nation community located in northern Ontario, 53˚31 59 N and 88˚36 21 W. The KLFN diesel plant consists of three generators, rated at 400, 600 kW, and 1 MW, using a single-unit dispatch strategy under normal operating conditions [14,15]. Currently, the community and utility have plans to increase capacity by installing a 1.6 MW generator likely over the next year. The local utility and community are rather familiar with RE projects, since WT and solar PV units have been deployed. The detailed information obtained for this case study is based on the collaboration efforts among Hydro One Remote Communities Inc. (HORCI), the community, and the authors. Kyocera, The solar PV panels considered are 230 kW, 220 kW Sanyo, 230 kW and 240 kW Canadian solar modules. The solar inverters are 6.3 kW, 10 kW, 10 kW, and 10 kW. Also, the WT used are 50 kW; 60 kW, 95 kW, and (2×100 kW) Northern Power; 30 kW; and 10 kW WTs. The equipment was selected since these units are commercially available in Canada and can potentially be transported to the community (e.g., 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 as follows: SC for the community-owned buildings where load data are available (i.e., school and water treatment plant), and AFC for the rest of the load. The model assumes that project investments take place at the start of each year, while their operation does not start until the middle of the year. The model is implemented in MATLAB using a genetic algorithm from the Global Optimization Toolbox to solve the MINLP problem.

The capital costs are based on information from previous RE equipment deployed in the last 2 years at KLFN, which, due to the location of the community, are higher than RE deployment costs in more accessible locations. Thus, for solar PV in Canada, the average price for on-grid turnkey projects ranged between $2800/kW and $5000/kW, but for off-grid systems it was $8100/kW in 2012. In the case of WTs in Canada, the average cost for turnkey large WTs projects was $2259/kW in 2013, while for small on-grid WT, the average price ranged between $6000/kW and $8000/kW in 2008. Note that the WT selection criteria must consider the wind regime; hence, in the case of KLFN, due to its low wind potential, a commercial WT was selected to make WTs economically feasible [16-19]. For RCs with higher wind speed regimes, different WT classes would have to be considered in the planning process.

Scenarios

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

1.Funding alternatives: Scenario 1 consider the baseline where one stakeholder funds the total projects cost. Scenario 2 incorporates a loan alternative to finance the projects, since initial economic resources are likely to be limited [20-23]. Scenarios 3–12 consider the loan alternative plus external government funding aimed to promote northern development available for community-driven projects.

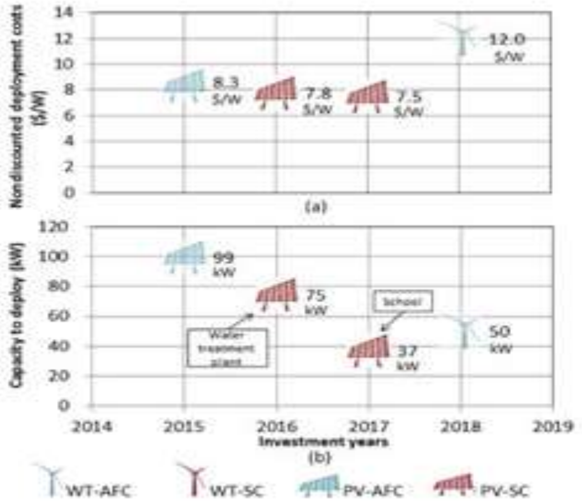

Figure 2. Scenario 3. RE long-term plan: (a) deployment costs and (b) capacity.

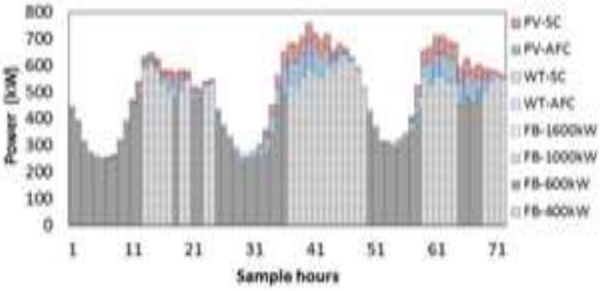

Figure 3. Power output per generator type for Scenario 3 (June 23–25).

2. Discount rate: 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.

3. Fuel cost growth: Scenario 6 considers a 5 % annual growth rate for the diesel-fuel cost which is equal to the historical average of the 10 year compound growth rate for fuel prices in northern Ontario since 2000.

Scenario 7 considers a higher rate, 7 % cost growth, and all other scenarios use a 4.5 % annual growth, the 5 year historical compound growth rate.

4.RE capacity limit : Scenario 8 eliminates the internal combustion installed capacity constraint described . For all other scenarios, the RE installed capacity limit is set to 50 % of the annual average community load.

5.Solar irradiation: Scenarios 9 and 10 represent the respective lower and upper expected variation limits for the annual average solar global irradiation [24-26]. Based on the correlation data available for a similar latitude location, the variation considered is approximately ±6 %. For the rest of the scenarios, an annual average of 2.9 kWh/m^2/day is assumed.

6. Wind speed: Scenarios 11 and 12 analyze the effect of lower and higher wind speeds, ±10 %; however, based on the mesoscale correlation information and performance of the currently installed WTs, the actual value is closer to the lower bound. The rest of the scenarios are based on an annual average of 5.61 m/s

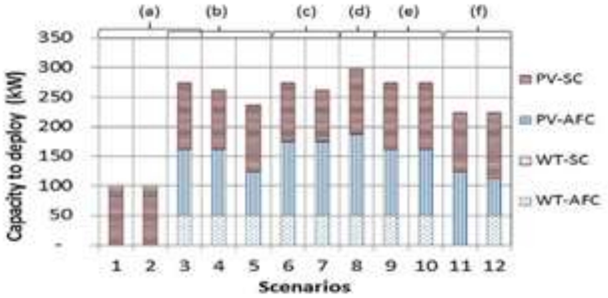

Figure 4. Cash-flow for Scenario 3.

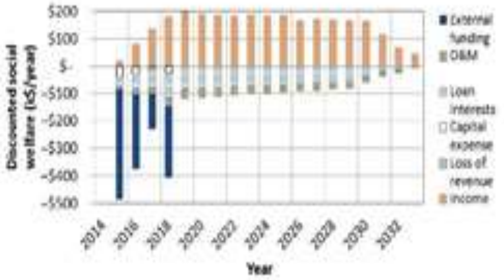

Figure 5. Proposed RE deployment capacity per scenario.(a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, (f) wind speed levels

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 the 12 selected scenarios.

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, highlighting the benefits of assessing multiple projects over a planning horizon.

Fig. 2(a) shows the solar PV cost reduction over the years resulting from the CB process considered by the model, which intrinsically promotes further solar PV deployment.

Fig. 2(b) presents the proposed installed capacity for each type of project and operation scheme. In this case, both 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 %).

Fig. 3 presents the power supplied per type of generation unit for three sample days; the FG units switch accordingly between high and low load requirements, as expected, where RE can be considered a negative load due to the low penetration level, having a maximum hourly and highest annual RE contributions of 35 % and 7 % over the planning horizon, respectively.

Fig. 4 shows the components of the annual social welfare 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 [27]. 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 repayment schedule. The intention of the loan is not only to obtain financial feasibility but also to be a commitment to maintain the equipment operational and invest in the relatively high costs, which, in this case, corresponds to approximately.

Summary of All Scenarios: Fig. 5 shows the proposed RE deployed capacity by technology and operating scheme for each scenario. Scenarios 1 and 2 are the most limited 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 3–12 consider external funding, thus reducing the community project expenses, and resulting in higher feasible RE deployment capacities [28]. 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 % has an installed capacity difference of only 12 kW; the reason for the relatively minor change is that the current subsidy frame-work decreases the direct effect of fuel price in the electricity rate. Scenario 8 proposes RE projects of 300 kW capacity when no predefined installed capacity limit is set, which corresponds 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. 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. Note that for all scenarios presented, the technological risks are similar, since the type of equipment to be deployed is the same and only the RE installed capacity changes. Fig.6 presents the Internal Return Rates (IRR) values from the community perspective for each type of project and scenario. Scenarios 1 and 2 have relatively low IRR values without even considering the parameter variation in the remaining scenarios and, as a result, are not attractive alternatives.

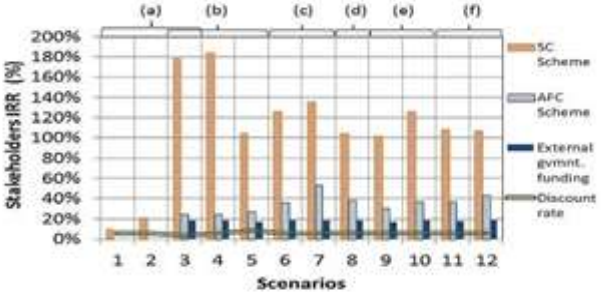

Figure 6. Expected IRR per stakeholder and scenario: (a) funding alternatives, (b) discount rates, (c) fuel costs, (d) no RE deployment limit, (e) solar irradiation levels, (f) wind speed levels.

On the other hand, Scenarios 3– 12 have significantly higher IRR, due to the partial contribution of 50 % of the capital expenses coming from the government agency, and thus the community capital costs are halved, while still obtaining the total economic benefit from the proposed projects. Furthermore, due to the same funding contribution, the potential loan is also reduced for Scenarios 3–12, which also reduces the annual loan payments and thus further contributes to an increase in the IRR values. This figure also shows the IRR for the received government funding when considering that government fuel subsidies are also reduced. In Ontario, approximately 66 % of the total fuel cost in 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. Therefore, from a policy perspective, supporting such remote RE projects would also benefit the government on top of other social benefits. It should be noted that as RE is further integrated into RCs, there will be a need to account for the potential benefits in the rate structure itself; this would require further study, and is not addressed in this paper.

Conclusion

A novel RE long-term planning model for RCs has been presented in this paper. The proposed model can be used to evaluate several RE projects through multiple years to obtain a long-term plan regarding RE development in RCs. The proposed model considers different operation schemes under which RE can be deployed, considering current economic and technical constraints. Furthermore, it considers community funding alternatives which results in higher economic feasibility for the community by sharing the risk among stakeholders. Finally, the model also allows quantifying the government benefit from supporting such projects under a given energy subsidy framework.

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**.** The model should be applicable to RCs in jurisdictions with similar characteristics as Canadian RCs, such as in Alaska and Chile.

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