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# Quantifying the Environmental and Economic Performance of Remote Communities

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**Abstract**
Remote communities such as oil production sites, post-disaster housing camps, and military forward operating bases (FOB) are often detached from established infrastructure grids, requiring a constant resupply of resources. In one instance, a 600-person FOB required 22 trucks per day to deliver necessary fuel and water and remove generated wastes. This logistical burden produces negative environmental impacts and increases operational costs. To minimize these consequences, construction planners can implement sustainability measures such as renewable energy systems, improved waste management practices, and energy-efficient equipment. However, integration of such upgrades can increase construction costs, presenting the need for a tool that identifies tradeoffs among conflicting criteria. To assist planners in these efforts, this paper presents the development of a novel remote site sustainability assessment model capable of quantifying the environmental and economic performance of a set of infrastructure alternatives. Through field data and literature estimates, a hypothetical FOB is designed and evaluated to demonstrate the model's distinctive capability to accurately and efficiently assess construction alternatives. The proposed model will enable construction planners to maximize the sustainability of remote communities, creating sites that are more self-sufficient with reduced environmental impacts.

*Keywords: Sustainability, infrastructure, remote communities*

## 1. Introduction

Remote communities such as oil production sites, post-disaster housing camps, and military forward operating bases (FOB) are often detached from established infrastructure grids, requiring a constant resupply of resources. Their inefficient, resource-dependent infrastructure yields a significant logistical burden, which creates negative environmental impacts and increases operational costs. For example, in 2004, a set of 21 remote communities in northern Canada relying on diesel generators required an energy output of 50 gigawatt-hours (M. Arriaga, Canizares, & Kazerani, 2013). Operating these generators cost $40M and emitted 40,000 tons of carbon dioxide ($CO_2$) – the equivalent annual emissions of nearly 8,000 passenger vehicles. Accordingly, remote community construction planners are presented with the challenging task of evaluating the impacts of their infrastructure alternatives in order to minimize environmental impacts while also minimizing costs.

A number of research studies have been conducted that: (1) evaluate sustainability challenges faced by remote communities; and (2) quantify the environmental impact of infrastructure alternatives. First, several studies were conducted that identified sustainability challenges at remote communities and proposed mitigation efforts. The Strategic Environmental Research and Development Program (SERDP) analyzed the

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financial, environmental, and safety costs associated with United States (US) military FOB design and operation (Noblis, 2010). The report proposed reducing resource consumption, minimizing waste through reuse, and incorporating more energy-efficient technology as areas for future research investment. Another source quantified FOB resupply requirements and evaluated infrastructure alterations to minimize logistical resupply (Putnam, Kinnevan, Webber, & Seepersad, 2016). Additionally, Arriaga et al. (2013; 2014) identified more than 280 northern and remote communities in Canada with limited or no access to electrical grids. The authors demonstrated that incorporation of renewable energy measures such as wind and solar systems may reduce fuel consumption and offset high operating costs and $CO_2$ emissions.

Second, numerous studies have computed the environmental impact of infrastructure alternatives for remote communities, including power production (M. Arriaga et al., 2013; Craparo & Sprague, 2018; WNA, 2011), water production (Cave, Goodwin, Harrison, Sadiq, & Tryfonas, 2011; Vince, Aoustin, Bréant, & Marechal, 2008), solid waste management (Batool & Chuadhry, 2009; Cherubini, Bargigli, & Ulgiati, 2009), and wastewater management (El-Fadel & Massoud, 2001; Racoviceanu, Karney, Kennedy, & Colombo, 2007). Further, additional studies have generated combinations of infrastructure alternatives that deliver optimal tradeoffs between environmental performance and cost through multi-objective optimization (Abdallah & El-Rayes, 2016; El-Anwar, El-Rayes, & Elnashai, 2010; Karatas & El-Rayes, 2016; Ozcan-Deniz, Yimin, & Ceron, 2012).

Despite the contributions of the aforementioned studies, there is no reported research that focused on quantifying tradeoffs between environmental and economic performance of remote community infrastructure alternatives. Accordingly, this paper presents the development of a novel remote site sustainability assessment model capable of quantifying the environmental and economic performance of a set of infrastructure alternatives in order to assist planners in maximizing the sustainability of remote community design.

The following sections of this paper describe: (1) selecting relevant decision variables; (2) formulating objective functions; (3) defining model constraints; (4) identifying model input data; and (5) evaluating model performance through an application example.

## 2. Model Formulation

This section presents the development of a model capable of quantifying the environmental and economic performance of remote community planning and construction. The development of this model includes identifying remote community decision variables and formulating sustainability objective functions.

### 2.1 Decision Variables

The decision variables utilized in the following model are selected to represent the infrastructure types required to support remote community facilities that have the greatest impact on sustainability objectives. The model considers the following types of infrastructure: (1) power production; (2) potable water production; (3) solid waste management; and (4) wastewater management. Within each type of infrastructure, multiple alternatives may be considered, and at least one alternative must be selected. For example, the function of solid waste disposal may be met with either incineration or landfilling. Table 1 in the application example summarizes potential alternatives within each type.

### 2.2 Objective Functions

For each decision variable alternative, the present model quantifies resource inputs and outputs that impact sustainability. For example, each of the aforementioned solid waste disposal alternatives have a requirement-driven input (volume of waste, gallons of fuel, etc.) and an environmental impact output (such as greenhouse gas (GHG) emissions). Each alternative also has an associated cost. While incinerator equipment may have a higher up-front cost than a landfill, its resulting GHG emissions may be less than an untreated landfill for the same volume of waste.

The first objective function is designed to quantify the impact that a remote community's infrastructure has on its surrounding environment. Measured in volume of equivalent carbon dioxide emissions (metric tons $CO_2E$/day), Equation (1) calculates the environmental impact for each infrastructure alternative as a function of its energy consumption and resource transportation requirements. Equation (2) calculates the environmental impact of a set of alternatives (i.e. remote community site). Emissions due to energy consumption are calculated as a function of daily fuel or power consumption (tons of $CO_2$/gallon diesel fuel or tons of $CO_2$/kW). The impact of resource transportation via ground is calculated as a function of vehicle efficiency (km/gal) and distance traveled (km). Resource transportation via air is calculated with Equation (3) a function of aircraft efficiency, distance traveled, and cargo transported. Increasing volumes of $CO_2$ correspond to increasingly negative impacts on the environment.

$$EI_i = EI_i^{ec} + EI_i^{rt} \quad (1)$$

$$EI_{site} = \sum_{j=1}^{J} EI_{ij} \quad (2)$$

Where EI = environmental impact (tons $CO_2E$/day);
i = infrastructure alternative;
j = infrastructure type;
J = total infrastructure types;
site = set of one infrastructure alternative for each infrastructure type;
$EI^{ec}$ = environmental impact due to energy consumption (tons $CO_2E$/day); and
$EI^{rt}$ = environmental impact due to resource transportation (tons $CO_2E$/day).

$$EI^{rt}(air) = EF_{air} * cargo_{air} * distance_{air} \quad (3)$$

Where $EI^{rt}(air)$ = environmental impact of resource transportation via air (tons $CO_2$);
$EF_{air}$ = emissions factor of aircraft (tons $CO_2$/ton cargo/km);
$cargo_{air}$ = cargo transported via air (tons); and
$distance_{air}$ = distance traveled via aircraft (km).

The second objective function quantifies the economic performance of a set of remote community infrastructure alternatives. Equation (4) accounts for initial, operating, and maintenance costs of each infrastructure alternative computed in cost per day ($/day). Equation (5) calculates the total cost of a set of infrastructure alternatives. Initial costs are calculated as a function of purchase, delivery, and setup costs per day of site duration. Operating costs are calculated as a function of fuel consumption, contractor costs, manpower, materials, and daily transportation costs. Maintenance costs are a function of manpower and materials required to maintain the asset's working condition.

$$TC_i = TC_i^{ic} + TC_i^{oc} + TC_i^{mc} \quad (4)$$

$$TC_{site} = \sum_{j=1}^{J}(TC_{ij}) \quad (5)$$

Where TC = total cost of all infrastructure alternatives ($/day);
i = infrastructure alternative;
j = infrastructure type;
J = total infrastructure types;
site = set of one infrastructure alternative for each infrastructure type;
$TC^{ic}$ = initial purchase and setup cost ($/day);
$TC^{oc}$ = operating cost ($/day); and
$TC^{mc}$ = maintenance cost ($/day).

### 2.3 Model Constraints

The present model is designed to consider and comply with all remote site characteristics. Resource requirements are dependent upon the population, duration and identified planning factors, which enables the results to be scaled appropriately. Environmental impacts and costs due to resource transportation are dependent upon the site location, available transportation method, and resource weight, which enables the model to apply to various locations. Further, the model is designed such that each alternative may be combined with any other alternative. For example, each potable water production system may be powered by any of the available power generation alternatives.

## 3. Model Input Data

Remote community construction planners must identify all remote site characteristics, planning factors, and infrastructure alternative data. Remote site data includes: (1) required personnel (persons); (2) location; (3) duration (days); (4) delivery method (ground, air, or sea); and (5) distance to commercial utilities (km). Planning factor data includes: (1) power requirement (kW/person); (2) potable water requirement (gal/person); (3) solid waste production (kg/person); and (4) wastewater production (gal/person). Infrastructure alternative data includes: (1) feasible alternatives for each infrastructure type (power production, potable water production, wastewater management, and solid waste management); (2) resource production rate (kW/day, gal/day, or kg/day); (3) resource consumption rate (kW/day, gal/day, or kg/day); (4) emissions factors (tons $CO_2$/kW or tons $CO_2$/gal); and (5) costs ($/unit, $/gal, or $/man-hour).

In order to effectively evaluate the environmental and economic life-cycle costs of infrastructure, boundaries must be identified and consistently adhered to. The present model was assumed to be bounded such that the environmental impacts and costs associated with the purchase and operation of each infrastructure alternative within the remote community are accounted for. Transportation from the alternative's primary distribution source (such as ground transportation from local town or air transportation from major metropolis or supplier) was also included, as these factors can have significant impacts on an alternative's performance. Production of resources and equipment off-site or by entities other than the remote community were not considered.

## 4. Application Example

In order to demonstrate the model's unique capability, a hypothetical military FOB is designed, and multiple infrastructure alternatives and durations are evaluated according to the proposed objective functions. A military base was chosen for the following example due to the availability of resource planning factors and historical data. This case study was designed to simulate a typical, mid-sized FOB in Southwest Asia. For this example, the required input data includes: (1) remote site characteristics; (2) planning factors; and (3) infrastructure alternative data. First, remote site characteristics include a 500-person remote community in Southwest Asia that must sustain living conditions for 180, 365, or 730 days. Common resources such as potable water may be transported via land from a local city center 24 km to the community. Uncommon resources such as solar panel equipment, military generators, and incinerators may be transported via air from a supplier located in Central Europe, 5,172 km from the community. Second, planning factors were identified for power, potable water, solid waste, and wastewater through historical data and US Army design guides (Noblis, 2010). Third, infrastructure alternatives and their consumption rates were identified through various sources, as seen in Table 1. Throughout the case study, energy consumption emissions factors were held constant to ensure consistency in results (US EPA, 2018).

**Table 1.** Sample infrastructure alternative data

| | Data | Value | Units | Source |
|---|---|---|---|---|
| **Site characteristics** | Personnel | 500 | | |
| | Location | Southwest Asia | | |
| | Duration | 180/365/730 | days | |
| | Distance for ground transport | 65 | km | |
| | Distance for air transport | 5172 | km | |
| **Planning Factors** | Power requirement | 1 | kW/person/day | (Noblis, 2010) |
| | Potable water requirement | 35 | gal/person/day | (Noblis, 2010) |
| | Solid waste production | 4.53592 | kg/person/day | (Noblis, 2010) |
| | Wastewater production | 35 | gal/person/day | (Noblis, 2010) |
| **Alternatives** | **Energy Production** | | | |
| | Mobile Electric Power Unit (MEP-806) | 60 | kW/unit | (635 MMG, 2017) |
| | Basic Expeditionary Airfield Resource Power Unit (BPU) | 800 | kW/unit | (635 MMG, 2017) |
| | Solar Panels | varies | | (Noblis, 2010) |
| | **Potable Water Production** | | | |
| | Reverse Osmosis Water Purification Unit (ROWPU) | 30,000 | gal water/day | (Gibbs, 2012a) |
| | Import water tankers | varies | | (Noblis, 2010) |
| | Import bottled water | varies | | (Noblis, 2010) |
| | **Wastewater Disposal** | | | |
| | Export off-site | varies | | (Noblis, 2010) |
| | Sewage lagoons | varies | | (Gibbs, 2012b) |
| | **Solid Waste Disposal** | | | |
| | Incineration | 36 | gal fuel/ton waste | (Putnam et al., 2016) |
| | Landfill | varies | | (Gibbs, 2012c) |
| | **Emissions Factors** | | | |
| | Electricity | $7.07 \times 10^{-4}$ | ton $CO_2$/kWh | (US EPA, 2018) |
| | Diesel | $1.02 \times 10^{-2}$ | ton $CO_2$/gal fuel | (US EPA, 2018) |
| | Aircraft | $4.10 \times 10^{-2}$ | ton $CO_2$/ton cargo/km | (Chao, 2014) |

By considering one alternative per each of the four infrastructure types, the developed model was used to generate 36 unique sets of infrastructure alternatives (i.e. sites). For each distinct duration, the model identified the associated EI and TC tradeoffs of each site. Figures 1, 2, and 3 display the set of solutions generated for 180-, 365-, and 730-day durations, respectively. For each duration, a set of notable solutions is highlighted in Table 2. In Figure 1, site S7 represents the solution with the lowest EI (20.23 tons $CO_2$/day), while site S34 represents the solution with the highest EI (39.74 tons $CO_2$/day) for a duration of 180 days. Conversely, site S4 represents the lowest TC ($27,477.31/day) and site S33 represents the highest TC ($115,717.41/day). Durations this short favor infrastructure alternatives with lower up-front environmental impacts and costs. For example, of the three feasible energy production alternatives, the MEP-806 generator produced the lowest $EI^{rt}$. Therefore, it resulted in the lowest total EI even though it had the highest $EI^{ec}$.

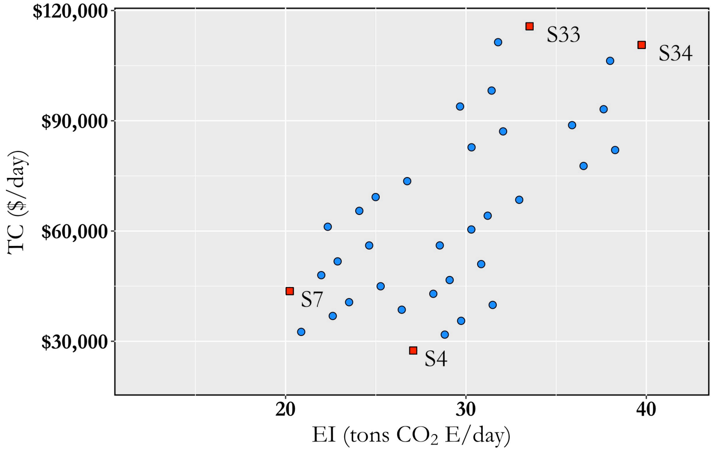


*Figure 1. Site solutions for 180-day duration*

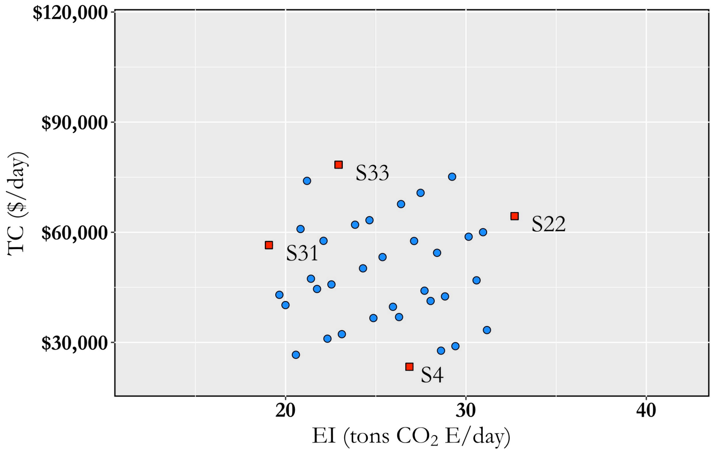


*Figure 2. Site solutions for 365-day duration*

With an increased duration of 365 days, Figure 2 shows that the minimum and maximum EI solutions switched to S31 (19.08 tons $CO_2$/day) and S22 (32.70 tons $CO_2$/day), respectively, due to varying energy production alternatives. While the solar panel alternative was found to result in the highest EI and highest TC at 180 days, it was found to have the lowest EI and highest TC at 365 days. This is likely due to the solar panels' high initial transportation requirement and low daily energy consumption. Consequently, as site duration increases, alternatives with higher up-front investments may become environmentally feasible if they produce less emissions per day.

Further, when the site's duration was increased to 730 days as seen in Figure 3, the minimum and maximum TC solutions shifted to S28 ($21,201.91/day) and S21 ($64,804.67/day), respectively. At this duration, solar panels were found to result in the lowest EI and lowest TC. Again, the alternative's high initial investment became less apparent over time due to its low operating and maintenance costs. Of note, incineration as a solid waste management alternative was found to have a lower EI and higher TC than landfilling at each duration. Meanwhile, importing bottled water and exporting wastewater off-site were consistently found to result in both the highest EI and highest TC, making them the least sustainable potable water production and wastewater management methods. Moreover, the EI and TC of each solution, on average, dropped 6.05 tons $CO_2$/day and $20,284.23/day when the duration was extended from 180 to 730 days.

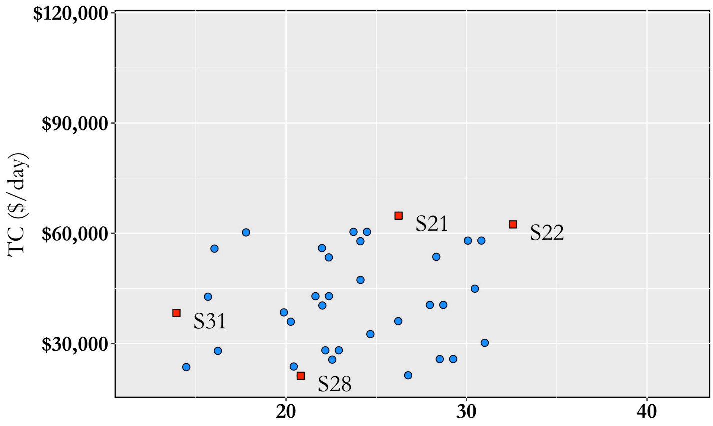


*Figure 3. Site solutions for 730-day duration*

**Table 2.** Summary of notable solutions

| | 180-Day Duration | | | |
|---|---|---|---|---|
| | **S7 (lowest EI)** | **S34 (highest EI)** | **S4 (lowest TC)** | **S33 (highest TC)** |
| **Energy Production** | MEP-806s | Solar Panels | MEP-806s | Solar Panels |
| **Potable Water Production** | Import water tankers | Import bottled water | ROWPUs | Import bottled water |
| **Wastewater Disposal** | Sewage lagoons | Export off-site | Sewage lagoons | Export off-site |
| **Solid Waste Disposal** | Incineration | Landfill | Landfill | Incineration |
| **EI** | 20.23 | 39.74 | 27.08 | 33.53 |
| **TC** | $43,657.49 | $110,643.58 | $27,477.31 | $115,717.41 |

| | 365-Day Duration | | | |
|---|---|---|---|---|
| | **S31 (lowest EI)** | **S22 (highest EI)** | **S4 (lowest TC)** | **S33 (highest TC)** |
| **Energy Production** | Solar Panels | BPUs | MEP-806s | Solar Panels |
| **Potable Water Production** | Import water tankers | Import bottled water | ROWPUs | Import bottled water |
| **Wastewater Disposal** | Sewage lagoons | Export off-site | Sewage lagoons | Export off-site |
| **Solid Waste Disposal** | Incineration | Landfill | Landfill | Incineration |
| **EI** | 19.08 | 32.70 | 26.87 | 22.94 |
| **TC** | $56,504.94 | $64,408.93 | $23,356.77 | $78,390.41 |
| | **730-Day Duration** | | | |
| | **S31 (lowest EI)** | **S22 (highest EI)** | **S28 (lowest TC)** | **S21 (highest TC)** |
| **Energy Production** | Solar Panels | BPUs | Solar Panels | BPUs |
| **Potable Water Production** | Import water tankers | Import bottled water | ROWPUs | Import bottled water |
| **Wastewater Disposal** | Sewage lagoons | Export off-site | Sewage lagoons | Export off-site |
| **Solid Waste Disposal** | Incineration | Landfill | Landfill | Incineration |
| **EI** | 13.93 | 32.57 | 20.81 | 26.23 |
| **TC** | $38,319.97 | $62,419.69 | $21,201.91 | $64,804.67 |

## 5. Summary and Conclusions

This paper presented the development of a novel remote site sustainability assessment model capable of quantifying the environmental and economic performance of a set of infrastructure alternatives for remote communities. An application example of a hypothetical military FOB was evaluated over three durations in order to demonstrate the model's unique capability. The model was able to quantify the environmental and economic performance of 36 distinct combinations of infrastructure alternatives for each duration and identify tradeoffs between performance objectives. The evaluation of increasing site durations demonstrated that over time, high initial investments may be offset by low operating costs. This capability will enable construction planners to evaluate the impacts of their infrastructure alternatives in order to minimize environmental impacts while also minimizing costs. The scope of this model can be expanded with the identification of additional infrastructure alternatives. Additionally, sustainability indexes may be utilized in order to further develop this model into a robust optimization tool capable of optimizing remote site location, environmental impact, and cost.

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