Optimal Deployment of Hybrid Alternative Power System at Signalized Intersections

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ABSTRACT

Traffic signal power failures can degrade the efficiency and safety at intersections that warrant traffic signal control. Alternative Power Sources (APS) are typically used to power traffic signals during power outages. Signals operating agencies need a decision making framework to identify optimal locations and deployment schedule for APS systems. This paper presents a methodology for optimal deployment of APS at signalized intersections with limited budget. This methodology can also be used to investigate the economic viability of using wind and solar energy as APS at a signalized intersection. Benefit-cost analysis is used as an economic tool, and optimization model is developed. The primary benefit of an APS is improving traffic operation efficiency and safety. The renewable sources, if harnessed, would add energy production and environment benefits. The methodology presented in this paper is generic and can be adapted to site specific condition by appropriately choosing the model inputs. A case study for a test network in Nebraska demonstrates the step by step implementation of the proposed methodology.

Keywords: Alternative power; Renewable energy; Traffic signals, Benefit-Cost analysis.
INTRODUCTION

Traffic control signal power failures can degrade the efficiency and safety of intersections that warrant traffic signal control. At nighttime, dark signals can result in even greater crash risk, as drivers may fail to perceive the presence of an intersection. A reliable traffic control system is indispensable to ensure uninterrupted operation at a signalized intersection.

Alternative power sources (APS), such as an Uninterruptable Power Supply (UPS) and battery system, can provide surge protection and backup power for traffic signals. The Manual of Uniform Control Devices (2009 edition) requires APS at intersections with traffic control signals interconnected with light rail transit systems, traffic control signals with railroad preemption or coordinated with flashing-light signal systems. Also, at other intersections with power issues, installing APS can potentially avoid the delay and improve safety. Currently, the UPS and battery system is the most prevalent technologies for APS used at signalized intersections (1). Wind turbine and solar panels has been used by transportation agencies all over the world for harnessing renewable energy (2). The state transportation agencies use wind and solar energy as APS for office buildings, maintenance facilities, welcome centers/rest areas, traffic management/logistics, and traffic signals, etc. (3). To implement appropriate APS applications, signals operating agencies need to identify project locations and appropriate deployment schedule.

This paper presents an optimization-based method for deploying APS in at signalized intersections with constrained budget. The authors also investigate the economic viability of using wind and solar energy as APS for signalized intersections by explicitly considering the context-sensitive economic impacts. The APS using wind/solar energy will be referred to as the Roadside Hybrid Power System (RHPS) in the following discussion. The RHPS includes a combination of wind turbine, solar panel and batteries. A successful deployment of RHPS requires comprehensive investigations of both infrastructural and economic viability. A methodology was developed to investigate whether this innovative application is worthwhile to implement at current deployment costs. This methodology can be used to answer the following important questions faced by decision makers:

1) What RHPS configuration is most cost-effective for a given network of signalized intersections given a budget constraint of X dollars?

2) What should be the schedule and configuration of RHPS installations over a period of N years with an availability of Y dollars per year?

The proposed methodology provides the number of battery bank, wind turbines, and solar panels—including no installation option—to be installed at a project site as a solution to the first problem identified above. For the second one, the solution includes the number of battery bank, wind turbines, and solar panels to be installed at each site in each year across the capital investment period. Optimization techniques are used to solve these problems.

Benefit-Cost Analysis (BCA) is used as an economic tool to consider the life-cycle benefit and cost of RHPS. BCA models can best examine the impact of an innovative technology, and the subsequent sensitivity analysis can provide the key parameters that affect the project net benefits (4). Benefit-Cost Ratio (BCR) and Net Present Value (NPV) are used as decision-making criteria. The benefits of APS are evaluated by accounting for losses in operational efficiency and safety, as well as environmental costs. The benefit as backup power for traffic signals is defined as power backup benefit. Additional benefit accrued through the use of renewable energy are the energy production and the reduction of greenhouse gas emission by
generating clean electricity, which is termed as renewable energy benefit. The remainder of the paper is organized as follows: The next section describes the formulation of the optimization problems and presents techniques to evaluate the benefits and costs associated with RHPS deployment. Then, a case study is presented based on a network in the Nebraska, with discussions of results and associated insights.

**PROBLEM FORMULATION AND SOLUTION METHODOLOGY**

The RHPS includes three base classes of configuration: (i) a battery backup system only, (ii) a decentralized wind/solar power generation system that sells all energy production to the utility agency but does not supply signal operations, and (iii) a hybrid power generation and backup system that includes wind/solar power generation along with a battery backup system. The wind turbine and solar panel are designed to be mounted on existing traffic signal poles. Structural analysis conducted in a previous study (5) showed that most of the traffic poles meeting AASHTO standards are strong enough to afford one small wind turbine (75 pounds) and two solar panels (15 square feet and 35 pounds each). One battery bank is designed for RHPS, and the capacity is enough to supply the signals for 4 to 6 hours at 700 watt load. At an intersection with four structurally stable traffic poles, there are 90 [2 (0 or 1 battery banks) × 5 (0 to 4 wind turbines) × 9 (0 to 8 solar panels)] possible design alternatives.

Accommodating renewables at signalized intersection is constrained by available infrastructure and renewable resources. A physical feasibility check should be done prior to the economic analysis. This paper focuses on economic analysis. BCA and optimization modules are developed for economic analysis. In BCA module, benefits and costs are estimated for all possible alternatives at each potential site. The BCRs are used to measure the economic viability of the alternatives. The potential benefits of an RHPS consist of power backup benefits and renewable energy benefits. The primary costs of an RHPS are identified as costs associated with initial investment cost of Operating, Maintenance and Repair (OM&R), financing cost, and the salvage value at the end of the project. Any other costs, required by an agency to better represent their requirements, can be easily added to the model. In this study, we assume the expected service life is equal to the analysis period. The BCR of a project alternative is calculated using equations 1, 2, and 3.

\[
\begin{align*}
    b_{ia} &= b^p_{ia} + b^r_{ia} \\
    c_{ia} &= c^v_{ia} + c^o_{ia} + c^f_{ia} - c^g_{ia} \\
    r_{ia} &= \frac{b_{ia}}{c_{ia}}
\end{align*}
\]

(1) (2) (3)

Where, \(i\) and \(a\) are subscribes for project site \((i)\) th project site) and design alternative \((a)\) th alternative out of 90 possible alternatives at one site, respectively; \(b_{ia}\) is the life cycle benefit of a design alternative \(a\) at site \(i\) including \(b^p_{ia}\) (power backup benefits) and \(b^r_{ia}\) (renewable energy benefits); \(c_{ia}\) is the life cycle cost of a design alternative \(j\) at site \(i\) that is a summation of \(c^v_{ia}\) (initial investment), \(c^o_{ia}\) (OM&R cost), \(c^f_{ia}\) (financing cost), and \(c^g_{ia}\) (salvage value); \(r_{ia}\) is the BCR of design alternative \(a\) at site \(i\). Design alternatives with a BCR greater than 1 are considered to be economically feasible. For a simple initial screening process, the projects can be prioritized in descending order of BCRs.

However, the BCR may favor projects with small costs and benefits over those with higher net benefits (6). In the case of a fixed budget, the prioritization by BCRs may leave a
large portion of the budget utilized. When the planning objective is to obtain maximum returns
within a certain budget, selected projects should provide a higher overall return, even though the
BCR ranking of a select project is lower. In these situations, the NPV is an appropriate selection
criterion, and is defined by the following equation:

\[ NPV_{ia} = b_{ia} - c_{ia} \]  \hspace{1cm} (4)

Where, \( NPV_{ia} \) is the NPV of design alternative \( a \) at site \( i \), and the other variables are the same as
defined earlier.

With the results from the physical feasibility check and the estimate of benefits and costs
from the BCA module, an optimization module is used to find the best possible projects to be
implemented that maximize the network-wide NPV, subjecting to budgetary constraints. The
optimization module identifies the number of battery banks, wind turbines, and solar panels to be
installed at each site to maximize the NPV for a given budget. The NPV of a network with \( h \)
potential sites can be estimated by equation 5:

\[ NPV = \sum_{i=1}^{h} \sum_{j=1}^{n} x_{ij} \left( b_{ij} - c_{ij} \right) - \sum_{i=1}^{h} c_{a} \times d_{i} \]  \hspace{1cm} (5)

Where, \( i \) is the subscribes for the project site, and \( i = 1, 2, \ldots h; j = 1, 2, 3 \) and represents the
option indices of battery bank, wind turbine, and solar panel; \( n \) equals 3 in this case; \( x_{ij} \) is the
number of option \( j \) to be installed at site \( i \); \( b_{ij} \) and \( c_{ij} \) are the life cycle benefits and costs of
option \( j \) at site \( i \); \( c_{a} \) is the base system cost of an RHPS, which includes but is not limited to the
costs of accessories, common power electronics used by all subsystems, and optional cabinet
housing the equipment; \( d_{i} \) is an indicator variable indicating the presence or absence of any form
of RHPS at a site \( i \), and

\[ d_{i} = \begin{cases} 1 & \text{if site } i \text{ is selected for RHPS installation} \\ 0 & \text{otherwise} \end{cases} \]  \hspace{1cm} (6)

The following equation 6 is used to calculate \( d_{i} \):

\[ d_{i} = \min \{ 1, \sum_{j=1}^{n} x_{ij} \} \]  \hspace{1cm} (6)

The problem formulation considers two scenarios in terms of budget constraint. The first
scenario has a given budget for a one-time initial investment but no constraint on yearly
spending. The second scenario is designed for projects with budget constraints specified on
yearly spending amounts. For the first scenario, the solution of decision variable \( x_{ij} \) indicates the
number of battery banks (\( x_{ib} \)), wind turbines (\( x_{iw} \)) and solar panels (\( x_{is} \)) to be installed at site \( i \).
The model is established as follows:

Scenario 1:

Maximize \( NPV = \sum_{i=1}^{h} \sum_{j=1}^{3} x_{ij} \left( b_{ij} - c_{ij} \right) - \sum_{i=1}^{h} c_{a} \times d_{i} \)

\[ = \mathbf{t'}_{n \times 1} \times \begin{bmatrix} x_{1b} & x_{1w} & x_{1s} \\ \vdots & \vdots & \vdots \\ x_{hb} & x_{hw} & x_{hs} \end{bmatrix}_{h \times 3} \times \begin{bmatrix} b_{1b} & \ldots & b_{hb} \\ \vdots & \vdots & \vdots \\ b_{1s} & \ldots & b_{hs} \end{bmatrix}_{3 \times h} \times \mathbf{i}_{n \times 1} \]
\[-i'_{n \times 1} \times \begin{bmatrix} x_{1b} & x_{1w} & x_{1s} \\ i & \vdots & \vdots \\ x_{hb} & x_{hw} & x_{hs} \end{bmatrix}_{h \times 3} \times \begin{bmatrix} c_{b} \\ c_{w} \\ c_{s} \end{bmatrix}_{3 \times 1} \times \begin{bmatrix} d_{1} \\ \vdots \\ d_{h} \end{bmatrix} = i'_{n \times 1} \cdot X \cdot B \cdot i'_{n \times 1} - i'_{n \times 1} \cdot X \cdot C - c_{a} \cdot i'_{n \times 1} \cdot D \]

Subject to:

\[
\begin{align*}
\sum_{i} \sum_{j} x_{ij} c_{ij} + \sum_{l=1}^{h} c_{a} \times d_{l} & \leq l \\
x_{ij} & = 0 \text{ if } f_{ij} = 0 \\
0 & \leq x_{ib} \leq 1 & 0 & \leq x_{iw} \leq 4 & 0 & \leq x_{is} \leq 8 \quad \text{for all } i
\end{align*}
\]

Where, \( b_{ij}, c_{ij} \) and \( c_{a} \) are the same as defined earlier. \( X \) is a matrix with columns indicating the number of battery banks, wind turbines, and solar panels at \( h \) sites. \( B \) is a matrix with each row listing the benefits from one unit of battery bank, wind turbine, and solar panel at \( h \) sites. The elements in \( C \) give the present value of the life cycle cost of one unit of battery bank, wind turbine, and solar panel, respectively. \( D \) is a column vector whose elements are dummy variables indicating the presence or absence of any form of RHPS at candidate sites; \( f_{ij} \) is a dummy variable defining the physical feasibility of design alternative \( j \) at site \( i \), and its values would be coded with the results from the physical feasibility check. \( i \) is the budget; \( i \) is a vector that contains a column of ones. The constraints in equation 8 to 10 apply to budget constraint, physical feasibility constraint, and structural constraint respectively. Methods to estimate the benefits and costs of RHPS are described in the following paragraphs and the details can be found in a previous study (5).

The second scenario represents a situation where constraints are specified on yearly spending amounts and any possible unspent budget can be transferred to the following year. The objective is to achieve the maximum benefit during the analysis period by properly scheduling the installations of RHPSs across the funding period. At the end of the analysis period, the RHPSs not reaching expected service life would be sold at a salvage value. The project scheduling can be seen as scheduling the installations of battery bank, wind turbines, and solar panels. For an intersection with four traffic poles, it is possible to have 13 installations at most: one battery bank, four wind turbines, and eight solar panels. The decision variable is \( x_{ijk} \), which indicates the installation of an option \( j \) (battery, turbine, or solar panel) at site \( i \) in year \( k \), and

\[
x_{ijk} = \begin{cases} 
1 & \text{if option } j \text{ is to be installed at site } i \text{ in year } k \\
0 & \text{otherwise}
\end{cases}
\]

The problem can be formulated as equation 11 to 16.

Scenario 2:

Maximize \( NPV = \sum_{i=1}^{h} \sum_{j=1}^{n} \sum_{k=1}^{m} x_{ijk} (b_{ijk} - c_{ijk}) - \sum_{i=1}^{h} (c_{a} \times d_{i} + c_{s}) \)

Subject to:

\[
\begin{align*}
\sum_{i=1}^{h} \sum_{j=1}^{n} \sum_{k=1}^{m} x_{ijk} c_{ijk} & \leq \sum_{k=1}^{m} B_{k} \quad \text{for all } k \\
x_{ij} & = 0 \text{ if } f_{ij} = 0 \\
0 & \leq \sum_{k=1}^{m} x_{ibk} \leq 1 \quad \text{for all } i \\
0 & \leq \sum_{k=1}^{m} x_{iwk} \leq 4 \quad \text{for all } i
\end{align*}
\]
0 ≤ \sum_{k=1}^{m} x_{t_{sk}} ≤ 8 \text{ for all } i \quad (16)

Where, \( b_{ijk} \) and \( c_{ijk} \) are the benefit and cost of option \( j \) at site \( i \) from year \( k \) to the end of the analysis period; \( B_k \) is the budget at year \( k \); \( h \) is total number of project sites; \( n \) is the total number of options, and \( n = 3 \); \( m \) is the number of funding years and \( k \) is the subscript of funding year; \( f_{ijk} \) is the dummy variable recording the physical feasibility of option \( j \) at site \( i \) in year \( k \). The yearly budget constraints are expressed by equation 12. Equation 13 is the physical feasibility constraint, and the structural constraints expressed by equations 14 to 16 limit the numbers of battery banks, wind turbines, and solar panels at one site. These integer optimization problems were solved by genetic algorithm (GA). GA is stochastic and has a better chance to search over the entire design space; therefore it has a very high likelihood of identifying a globally optimal solution (7).

The following section outlines the methodology to estimate benefits for the RHPS.

**Power Backup Benefits**

The power backup benefits include travel time savings, accident cost savings, and vehicle operation cost savings (8). The methods used in this paper were selected keeping in mind that the analyses would be conducted at the planning stage with a limited availability of a high resolution traffic data. The present value of life cycle power backup benefits at a project site \( i \) \( (e^b_i) \) can be estimated by the following equation:

\[
e^b_i = \sum_{k=1}^{m} \frac{e^b_{ik}}{(1+d)^{k-1}}
\]

(17)

Where, \( e^b_{ik} \) is the power backup benefit at site \( i \) in year \( k \), and \( m \) is the expected service life; \( d \) is the real discount rate.

**Travel time savings**

In this study, the delay caused by AWSC operation is compared to that of full operation to estimate the travel time savings. The monetized travel time savings are obtained by multiplying incremental system delay and the value of time.

In preliminary analysis, it may not be practical to conduct an engineering study at each intersection. In this case, the quick estimate method in the *Highway Capacity Manual 2010* edition (HCM 2010) can be used to estimate delay. The average delay per vehicle at AWSC intersections can also be estimated by empirical delay models using volumes data (9).

**Accident cost savings**

Dark signals can potentially be hazardous for drivers. A direct way to estimate accident cost savings is to use crash records related to dark signals. In the absence of such data (which is generally the case), empirical models can be used. For example, the National Cooperative Highway Research Program (NCHRP) developed methodologies for predicting Total Injury Crashes (TIC) at stop-controlled and signalized intersections using Annual Average Daily Traffic (AADT) data as an input variable (10). The reduction in the number of crashes can then be multiplied by the average value of one crash for the region to estimate accident cost savings.
Operational cost savings

Operational cost savings are estimated by calculating savings in fuel consumption. Change in fuel costs can be estimated using a delay-based methodology provided in the manual of User and non-user benefit analysis for highways, which is often called the Red Book (8).

Other benefits

Another benefit from RHPS is the gaseous emission reductions resulting from reduced fuel consumption. The pollutants from vehicle fuel combustion can be estimated by fuel-based emission models or simulation (11). The monetary costs of air pollutants can be measured in three ways (12): i) as the cost of cleaning up the air near the source of degradation, ii) as the cost associated with addressing the effects of degradation, and iii) as the willingness of persons to pay to avoid the degradation. As there is no standard for air pollutant pricing, the price depends more on user preference.

Some other benefits discussed in the Red Book, such as the economic development impacts, are not included here, since they are unlikely to accrue significant benefits beyond those benefits discussed above. The values of these benefits can be added to the generic methodology if they are deemed critical for a specific cite.

Renewable Energy Benefits

Renewable energy benefits include energy production and reduction in greenhouse gas emissions by generating electricity from renewable sources rather than fossil fuels. For the planning of renewable energy projects, it is very critical to estimate energy production. Wind energy production can be estimated by the bin method with wind data and a turbine power curve (13). There are many software programs and on-line tools that can be used to predict wind and solar energy production. These benefits can then be monetized using ongoing electricity rates.

Electricity prices change over time; price escalation rates for the U.S. in future years are provided by the U.S. Federal Energy Management Program (FEMP) (14). The life cycle benefits from energy production at a project site \( (e_i) \) can be estimated as:

\[
e_i = Ap^e \times \sum_{j=0}^{t} \frac{I_{(2012+j)}}{(1+d)^j}
\]

Where, \( A \) is the average annual energy production (kWh) at site \( i \); \( p^e \) is the local electricity price at the base year 2012; \( I_{(2012+j)} \) is the projected average fuel price index given by FEMP (14) for the \( j \)th year from the base year 2012; the life cycle is \( t+1 \) years; \( d \) is the real discount rate.

Generating electric energy using renewable sources can reduce the emission from generating electricity using fossil fuels. Greenhouse gas emissions saved from renewable energy production can be estimated by the equation 19 below:

\[
E_m = P \times f_e
\]

Where, \( E_m \) is the amount of emission, \( P \) is the energy production in MWh, and \( f_e \) is the emission factor (lbs/MWh). The value of emission factors can be obtained from the Emissions & Generation Resource Integrated Database (eGRID) (15). For example, in Nebraska, the emission factor was 1,722.67 for CO\(_2\), 28.97 for CH\(_4\), and 29.19 for N\(_2\)O. The amounts of greenhouse gases must be converted to their carbon dioxide equivalent to calculate savings as a dollar value, using the following equation:

\[
E_{CO_2} = E_m \times GWP
\]
Where, $E_{CO2}$ is the CO$_2$ equivalent, $E_m$ is the amount of emission, and GWP is the Global Warming Potential. GWP is 1.0 for CO$_2$, 25 for CH$_4$, and 298 for N$_2$O (16). The annual carbon dioxide-equivalent in each analysis year can be estimated with the base year value and the projected carbon dioxide emissions rate indices for electricity by the FEMP (14). Then, greenhouse gas emissions savings can be calculated by multiplying the annual carbon dioxide-equivalent with the projected carbon dioxide-equivalent emissions prices.

CASE STUDY

The case study was conducted for the city of Kearney, Nebraska. Six intersections along 2nd Avenue and U.S. Highway 30 were considered for RHPS installation. Each intersection had four traffic signal poles structurally sound for RHPS installation. During the analysis period, traffic volumes in the study area were assumed to increase by 3% each year. A service life of 15 years was used for any type of RHPS, with the year 2012 as a base year. The battery bank had four 6V 305Ah batteries which could supply full signal operation for two hours at 700 watt load, and another four hours of flashing operation at a 350 watt load. This battery capacity specification is used by the Nebraska Department of Road for UPS at signalized intersections. The 1.0 kW wind turbine and 210 watt solar panels can be mounted traffic signal poles, and the battery system can be enclosed in a cabinet attached to the traffic cabinet. Structural feasibility checks were conducted to test the physical feasibility of using wind and solar energy. All six sites could potentially accept solar panel installation, but only sites 1 and 5 are suitable for turbine installation. For the economic analysis, a discount rate of three percent was used, as recommended by the Red book for the benefits and costs measured in constant dollars.

Power Backup Benefit Estimation

To study power outage and interruption history, power interruption records between April 2011 and April 2012 were retrieved from the UPS devices at these intersections. Periods when line power was not available or not qualified were considered as unavailable periods. Four analysis periods were used in accordance with the signal timing plan utilized at these intersections: a.m. peak (7:00-9:00), noon peak (11:00-13:00), p.m. peak (16:00-18:00), and off-peak (all others). The power failure distribution by time is shown in Figure 1. The longest outage duration at these intersections was 1.9 hours. The designed battery capacity was adequate to supply traffic signals for 4 to 6 hours of full operation. The annual average outage per customer was 32.9 minutes, as reported by local utility services. This outage duration was distributed to different times of day for each site following the distribution of line power unavailable time.

At the time of analysis, only AADT data and peak period volumes on each approach at the intersections were available. Delays during signal control and AWSC operations were estimated by the quick estimate method in the HCM 2010 and the empirical delay models for AWSC intersections, respectively (17). A local average hourly wage of $17.05, reported by the Nebraska Department of Labor, was used as the value of travel time in the base year. With the estimated delays, extra fuel consumption during AWSC operation was estimated by the delay-based fuel consumption model (8). The Nebraska average gasoline price for all grades in 2012 (18) was used as the base year fuel price and to estimate future prices in 2012 dollars via the projected average fuel price indices by FEMP (14).
Emissions from fuel combustion were then calculated using the fuel-based emission model \((8)\). The prices of \(\text{CO}_2\) in the analysis period were set based on the projected carbon dioxide-equivalent emissions prices used by FEMP \((14)\). The median marginal damage costs for NOx \((\$25/\text{ton/year})\) and VOCs \((\$180/\text{ton/year})\) estimated by Muller and Mendelsohn \((19)\) were chosen as the base year prices of pollutants.

Savings in police resources are also considered here. Police are often diverted for traffic guidance in the case of signal power failure. The RHPS can provide power supply and save police resources for other activities. In this case study, traffic directing time was assumed to be equal to outage duration. According to the Lincoln, Nebraska Police Department, the cost of police duty is $53 per hour, which was used as the unit cost of police traffic direction at the base year.

Total Injury Crashes models were used to predict the crash rate under both signal control and AWSC operation \((10)\), as no field data were available. The ratio of fatal and injury crashes to total crashes was calculated using crash statistics from the Nebraska Office of Highway Safety for the county where the project area was located. Crash cost data were also obtained to estimate the savings from eliminating one crash \((20)\); the average accident cost savings of eliminating one crash was about $39,000. This value was used as the cost of a crash at the base year.

In this analysis, the present value of future prices of travel time, crashes, and police direction were assumed to be equal to the base year prices. Figure 2 shows the average benefits for the entire network at the base year, assuming each intersection had a power backup system, and the first-year potential power backup benefits at the studied sites. The benefits were more favorable at intersections with high volumes. It should be noted that the dynamic traffic interactions between intersections were not considered. The power backup benefits vary every year due to increased traffic and price escalation.

**Renewable Energy Benefits Estimation**

To estimate wind and solar energy production, meteorological data including wind speed, air temperature, and solar radiation at the study sites were collected.
(a) Average power backup benefit per hour of outage in the base year.

(b) Average power backup benefit per hour of outage in the base year.

FIGURE 2 Power backup benefits at the base year.
A bin method is used to estimate energy production (15). The power curve provided by the wind turbine manufacturer provided only the ideal power outputs; here real-world data were used to model turbine power output. A test site in Lincoln, NE has been used for long-term data acquisition to assess the impacts of wind and solar energy as power for traffic signals. One 1.0 kW wind turbine and two 210 watt photovoltaic panels are installed at the site. A sensor board installed in the research cabinet collects wind and solar energy production data. The wind power curve from the Lincoln test site was used to estimate wind energy production at the study sites. With a 1-kW wind turbine, the potential wind energy production was estimated to be 145 kWh per month at site 1 and 128 kWh per month at site 5. The variation in solar radiation was minimal in the small study area. Site 5 had the lowest radiation among the six, and the solar energy production from one panel at this site was approximately 31 kWh per month, estimated by the radiation-power curve from the Lincoln test site. Greenhouse gas emissions saved from renewable energy production is estimated using equation 19 and 20.

**Benefit-Cost Analysis**

The project cost includes the installed cost of the system components and OM&R costs. The basic cost of an RHPS is $1,500. It would cost $1,352 to add a battery backup, $2,578 to add a wind turbine, and $350 to attach one solar panel. As the RHPS is designed to be low-maintenance, the annual OM&R cost was assumed to be 1.5% of the system installed cost excluding the basic cost. The financing cost was assumed to be zero in this analysis. The life cycle cost ($C_t$) at site $i$ can be estimated as:

$$C_t = C_{q,i} + 1.5\% \times (C_{q,i} - 1500) \times \frac{(1+d)^{N-1}}{d(1+d)^N}$$

(21)

Where, $C_{q,i}$ is the installed project cost at site $i$, $d$ is the discount rate, and $N$ is the number of years over which the annual OM&R cost recurs.

**Site Prioritization**

The six candidate sites have 906 choices of deployment plan. For a simple initial screening process, the BCA module calculated the BCRs for all 90 alternatives at each site, and gave a priority index for site prioritization. At the electricity price of 9.5 cents per kWh, the RHPS designs of grid-connected wind or solar power generation systems (no battery bank) were not economically viable at the study sites due to BCRs less than 1. For RHPS with both power backup and generation capability, the marginal BCR of adding one 210 watt solar panel to existing RHPS was approximately 1.03 at all sites. The BCR of adding one 1.0 kW wind turbine to an RHPS was 0.64 at site 1 and 0.56 for site 5. Thus, wind energy could not be used, as it was not economically feasible at the physically feasible sites 1 and 5.

**Optimal Deployment with Constraint on Initial Investment**

The initial investment is assumed to be $10,000, which will be spent in the first year of analysis. This investment does not include the OM&R cost, which is assumed to come from different funding sources. The salvage value is assumed to be zero if service life is reached. The problem is formulated as equation 22 to 25:
Maximize $NPV = \sum_{x} i'_{6 \times 1} \cdot XB \cdot i_{6 \times 1} - \left( 1 + 1.5\% \times \frac{(1 + d)^N - 1}{d(1 + d)^N} \right) i'_{6 \times 1} \cdot XC - c_d \cdot i'_{6 \times 1} \cdot D$

\[
= i'_{6 \times 1} \times \begin{bmatrix} x_{1b} & x_{1w} & x_{1s} \\ \vdots & \vdots & \vdots \\ x_{6b} & x_{6w} & x_{6s} \end{bmatrix} \times \begin{bmatrix} b_{1b} & \cdots & b_{6b} \\ b_{1w} & \cdots & b_{6w} \\ b_{1s} & \cdots & b_{6s} \end{bmatrix} \times i_{6 \times 1}
\]

\[= \left( 1 + 1.5\% \times \frac{(1+3\%)^{15} - 1}{3%(1+3\%)^{15}} \right) i'_{6 \times 1} \times \begin{bmatrix} x_{1b} & x_{1w} & x_{1s} \\ \vdots & \vdots & \vdots \\ x_{6b} & x_{6w} & x_{6s} \end{bmatrix} \times \begin{bmatrix} 1352 \\ \vdots \\ 2578 \\ 350 \end{bmatrix} \]

\[-1500 \cdot i'_{n \times 1} \cdot \begin{bmatrix} d_1 \\ \vdots \\ d_n \end{bmatrix} \]

\text{(22)}

Subject to:

\[i'_{6 \times 1} \cdot X \cdot C + 1500 \cdot i'_{6 \times 1} \cdot D \leq 10000 \quad \text{(23)}\]

\[f_{ij} = 1 \quad \text{(24)}\]

\[0 \leq x_{ib} \leq 1 \& 0 \leq x_{iw} \leq 4 \& 0 \leq x_{is} \leq 8 \quad \text{for all } i \quad \text{(25)}\]

All variables are the same as defined in equation 7 to 10. The problem was solved by GA using programs coded in Matlab. In the individual benefit-cost analysis, the BCRs of all design alternatives for sites 1 and 5 were found to be less than 1; $x_{ib}$ was 0 for all six sites, as wind energy was not physically or economically feasible. The BCR for battery backup system ($r_b$) and BCR for all installation at each site ($r$) are shown in Table 1.

**TABLE 1 Optimal Design Configuration for the Studied Sites**

<table>
<thead>
<tr>
<th>Site</th>
<th>p.m. Peak volume</th>
<th>Battery backup (unit)</th>
<th>Solar panel (unit)</th>
<th>$r_b$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2,139 vehicles /hour</td>
<td>1</td>
<td>0</td>
<td>1.18</td>
<td>1.18</td>
</tr>
<tr>
<td>3</td>
<td>3,851 vehicles /hour</td>
<td>1</td>
<td>0</td>
<td>4.45</td>
<td>4.45</td>
</tr>
<tr>
<td>4</td>
<td>1,963 vehicles /hour</td>
<td>1</td>
<td>4</td>
<td>1.80</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Sites 2, 3, and 4 were selected for battery backup systems, with BCRs ($r_b$) of 1.18, 4.45, and 1.54, respectively. At site 6, battery backup was shown to be desirable with a BCR of 1.03, but no installation was selected due to budget constraints. Site 4 was selected for solar panels with better energy performance than sites 1 and 2. The site BCR ($r$) decreased after the attachment of solar panels. The total benefit of the project was nearly $25,860 during the period between 2012 and 2027, and the life-cycle cost of the entire project was approximately $10,095. The installation sites had higher traffic volumes than the unselected sites. Site 3 had the highest individual BCR. This site had the highest traffic volume and power interruptions were more frequent, as depicted in Figure 1. Site 4 had more power interruptions during peak traffic periods, which resulted in a higher BCR with lower volume.

*Optimal Deployment with Yearly Budget Constraints*
Agencies sometimes have constraints on yearly budgets for infrastructure improvement. In this case study, a funding plan over a three-year period beginning in 2012, with capital outlay of $3,000, $4,000, and $3,000 (in constant base-year dollars), was assumed to be used for RHPS deployment. For the first two years, any unspent budget could be transferred to the following year. The analysis period is 15 years, and at the end, any RHPS systems not reaching the 15-year expected service life would be sold at a salvage value of 5% of installed cost. The installed costs for all components were assumed to be constant. The annual OM&R cost was assumed to be 1.5% of installed cost as defined earlier. The annual renewable energy production was assumed to be a constant over time. A project could not be invested in until the critical year when the BCR was greater than 1. From the results of BCRs, sites 1 and 5 were not qualified for any investment, so wind energy was not feasible in this project. For the other four sites, each one can have at most one battery bank and eight solar panels. The maximum NPV can be obtained by solving the following model:

\[
\text{Maximize } NPV = \sum_{i=1}^{4} \sum_{j=1}^{3} \sum_{k=1}^{3} [x_{ijk}b_{ijk} - (1 + 1.5\%)x_{ijk}c_{ijk}] \\
- \sum_{i=1}^{4} 1500 \times \min \left\{ 1, \sum_{j=1}^{3} \sum_{k=1}^{3} x_{ijk} \right\} \\
+ \frac{\sum_{i=1}^{4} \sum_{j=1}^{3} \sum_{k=1}^{3} 5\% x_{ijk} c_{ijk}}{(1+3\%)^{14}}
\]

Subject to:

\[
\sum_{i=1}^{4} \sum_{j=1}^{3} \sum_{k=1}^{3} x_{ijk} c_{ijk} \leq \sum_{k=1}^{3} B_k \quad \text{for all } k = 1, 2, 3
\]
\[
f_{ij} = 1
\]
\[
0 \leq \sum_{k=1}^{m} x_{ibk} \leq 1 \text{ for all } i
\]
\[
0 \leq \sum_{k=1}^{m} x_{iwk} \leq 4 \text{ for all } i
\]

All the symbols are as defined in equation 11 to 16.

The implementation solution is shown in Table 2. During the 15-year analysis period, the total net project benefit was approximately $24,840, while the project cost was approximately $10,445. The entire project BCR over the 15-year analysis period was approximately 2.4.

Compared to the first scenario, the three-year funding overlay produced fewer benefits than that of one-time investment within the same amount of funds. Here the yearly budget was expressed in base-year constant dollars, however, transportation agencies often allocate the budget by nominal values. When the amount of future funding is determined and the funding will be delivered each year by a nominal value, the actual money received will be less than the determined amount in base-year dollars.

**Sensitivity Analysis**

The renewable energy benefits did not raise the cost-effectiveness in this project due to low BCRs. The main factors affecting the cost-effectiveness of RHPS would be the electricity price, utility grid power availability, and the availability of renewable energy resources. In addition, for
renewable energy projects, there are some federal and state-level incentives that might reduce the project investment. A sensitivity analysis was conducted for site 1, assuming different power availability and utility prices. The 99.99% power availability represents the outage duration of 32.9 minutes used in the case study. The local price of 9.5 cents per kWh was compared to the high price of 14 cents per kWh in California. Table 3 lists the BCRs ($r$) for all five design configurations.

### TABLE 2 Implementation in Three Funding Years

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Battery backup (unit)</th>
<th>Solar panel (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2013</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2014</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### TABLE 3 Sensitivity Analyses on Incentive, Power Availability and Energy Cost

<table>
<thead>
<tr>
<th>Subsidy</th>
<th>Power availability</th>
<th>Electricity price ($/kWh)</th>
<th>$r_b$</th>
<th>$r_w$</th>
<th>$r_{-1s}$</th>
<th>$r_{-2s}$</th>
<th>$r_{-w,1s}$</th>
<th>$r_{-w,2s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.99%</td>
<td>99.99%</td>
<td>9.05</td>
<td>0.62</td>
<td>0.74</td>
<td>0.69</td>
<td>0.74</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>14.0</td>
<td>0.68</td>
<td>1.20</td>
<td>0.93</td>
<td>1.09</td>
<td>1.29</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>99.96%</td>
<td>9.05</td>
<td>3.95</td>
<td>2.49</td>
<td>3.44</td>
<td>3.09</td>
<td>2.35</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>14.0</td>
<td>4.32</td>
<td>3.11</td>
<td>3.93</td>
<td>3.66</td>
<td>3.01</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>99.55%</td>
<td>9.05</td>
<td>44.90</td>
<td>24.00</td>
<td>37.27</td>
<td>31.91</td>
<td>21.71</td>
<td>19.85</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>14.0</td>
<td>49.09</td>
<td>26.63</td>
<td>40.92</td>
<td>35.17</td>
<td>24.17</td>
<td>22.18</td>
</tr>
<tr>
<td>30%</td>
<td>99.99%</td>
<td>9.05</td>
<td>0.62</td>
<td>1.06</td>
<td>0.99</td>
<td>1.06</td>
<td>1.10</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>14.0</td>
<td>0.68</td>
<td>1.71</td>
<td>1.32</td>
<td>1.55</td>
<td>1.84</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td>99.96%</td>
<td>9.05</td>
<td>3.95</td>
<td>3.56</td>
<td>4.92</td>
<td>4.42</td>
<td>3.36</td>
<td>3.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.0</td>
<td>4.32</td>
<td>4.45</td>
<td>5.62</td>
<td>5.23</td>
<td>4.29</td>
<td>4.16</td>
<td></td>
</tr>
<tr>
<td>99.55%</td>
<td>9.05</td>
<td>44.90</td>
<td>34.28</td>
<td>53.24</td>
<td>45.59</td>
<td>31.02</td>
<td>28.36</td>
<td></td>
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<tr>
<td></td>
<td>14.0</td>
<td>49.09</td>
<td>38.04</td>
<td>58.46</td>
<td>50.25</td>
<td>34.53</td>
<td>31.69</td>
<td></td>
</tr>
</tbody>
</table>

$b =$ batteries only, $w =$ batteries + wind turbine, $1s =$ one panel, $2s =$ two solar panels, $w,1s =$ batteries + wind turbine + one solar panel, $w,2s =$ batteries + wind turbine + two solar panels.
The BCR of a battery backup system was very sensitive to grid power supply availability. At high power availability (99.99%), the battery backup system was not desirable. The results verified electricity price as a key parameter that determined the cost-effectiveness of a wind/solar energy project. Decentralized wind or solar power generation systems are economically viable in areas with high utility prices.

Discussion of Results

With improvements of the efficiency and decreasing prices of wind and solar generators, wind and solar energy could have greater potential to be integrated in the transportation infrastructure. At site 1, wind energy was shown more cost-effective than solar energy. However, in urban and suburban areas, zoning laws and building obstacles limited the application of wind energy. Sale of renewable energy was shown not to be a significant benefit compared to the power backup benefits for the study sites. Areas with lower grid power availability and lower electricity prices should consider the battery backup systems first, which has better chance to result in acceptable BCR and NPV.

The benefits estimated in the case study were conservative. The expected service life of 15 years was made less than its economic life. Impacts of the interactions between intersections were not considered. As a power outage is a random event, it could occur at any time of day. During an outage in peak traffic hours, the RHPS would produce more benefits than those produced during off-peak hours, assuming the durations are the same. Usually, dark signals cannot be recovered immediately when grid power becomes available. The losses of efficiency and safety during the time waiting for maintenance response were included as benefit of RHPS in this study.

CONCLUSIONS

This presented methodology can be used as decision assisting tool for accommodating wind and solar energy in roadway infrastructures. This design problem assumes that the agencies attempt to maximize their favorable benefits to users and nonusers. The most important task in BCA is the identification of relevant benefit and cost items to be included in analysis. Negative impacts of APS should also be taken into account if identified. The selection requires careful attention to capture the items that may have a significant impact on the outputs. Transportation agencies should verify the roadway APS using wind/solar energy is not adversely affecting highway safety and traffic flow, and integrating renewable energy in highway infrastructure requires adequate liability insurance to hold the Department of Transportation and FHWA harmless (21).

The optimization model used in case study is easy to solve. In the case of large-scale network applications, the formulation can be modified to meet requirements. The developed methodology can be used for single or multiple sites, and for any location using the site-specific traffic conditions, signal power supply profile, and meteorological data. The module for estimating power backup benefits could be used to evaluate the benefits of other types of traffic signal backup power. The module for estimating renewable energy benefits can be used to evaluate wind/solar energy projects within roadway infrastructure. By changing the benefit and cost items over time, the method can evaluate the impacts of a project over life cycle and with changes in economic and social conditions. It is also possible to add a weight for each cost and benefit item to reflect the user’s preference.
REFERENCES


