Optimal Deployment of Hybrid Alternative Power System at Signalized Intersections

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Optimal Planning for Traffic Signal Alternative Power Sources in Signal Network

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ABSTRACT

Dark signals and flash operation during traffic signal malfunction can degrade the efficiency and safety at an intersection warranting a signalized control. Alternative power sources, such as an uninterruptable power supply system, can provide power protection as well as power back-up to the traffic control systems. The policy makers, with limited budgets and unlimited demands, need a tool to choose signalized intersections that can be provided with backup power. They also need to decide the battery capacity at these intersections. At present, there exists no such tool that can help to make an optimal choice for capacity and installation of battery backup systems. This paper aims to estimate the economic impacts of traffic signal malfunction, and develop a decision support tool to optimize the investment plan of backup power. The methodology to estimate the benefits and costs of installing alternative power sources on urban arterials are presented and demonstrated by a case study conducted in Nebraska. The alternative power systems studied in the case study includes a wind turbine and several solar panels mounted on existing traffic poles, and a battery bank. Benefit-cost ratio is considered as decision making criteria. The benefits of the alternative power are stated as user benefits, non-user benefits and others. The primary benefit will be improving traffic network reliability. The renewable sources, if harnessed, would add advantages of cleaner energy and sale of excess production. The costs include initial investment, and operation and maintenance cost. The decision support problem can be solved using a discrete optimization model, which will identify the best installation intersections and the design combinations for each identified site. The solution will maximize the benefit-cost ratio under budget constraints. The proposed model can also be used to evaluate whether the project would warrant the return of investment and prioritize potential project sites. It can help to build safe and efficient transportation infrastructures, as well as promote renewable energy in transportation sector.

KEYWORDS: Alternative power, UPS, Traffic Control, Benefit-cost analysis.
INTRODUCTION

Dark signals caused by power outage and flash operation during traffic signal malfunction can degrade the efficiency and safety at an intersection warranting a signalized control. When traffic signals are inoperative, most states require reverting to All-Way Stop-Controlled (AWSC) intersection. During a signal malfunction, traffic signals are operated in the flash mode: a red flashing signal on both the major and minor approaches to the intersection (red/red flash) or a flashing yellow indication on the major approach and flashing red indication on the minor approach (yellow/red flash). If the signals are operated in red/red flash, it is often treated as AWSC. This operation mode treats the cross street movements more favorably, but the total intersection capacity is limited. The inoperative intersections would also result in risky operation as that drivers might not perceive the existing of the intersection and do not stop. Some drivers are confused by the right-of-way.

In a survey responded by eighteen traffic signals maintenance agencies in Georgia and twenty-one agencies in other states, 51% of malfunction flashing signals were caused by power interruption in Georgia, and 29% in nationwide. The line power from utility grid was the most frequent sources of damaging electrical surges to the signal controller. Alternative power sources, such as an Uninterruptable Power Supply (UPS) system, can provide power protection for the controller and serve as backup power during a grid power outage. Providing backup power at signalized intersections is an effective way to avoid the delays caused by reverting to all-way stop-control and maintain the safety during normal signal operation. The battery backup system is the most prevalent technology for responding to power outages at signalized intersections. In the 2009 National Manual on Uniform Traffic Control Devices (MUTCD), the traffic control signals interconnected with light rail transit systems, traffic control signals with railroad preemption or coordinated with flashing-light signal systems are required to have a backup power source. However, an alternative power source would be desirable at each signalized intersection if the benefit-cost ratio is favorable.

No research was found on the economic impacts of dark signals at intersections under medium to high volumes. Only several studies have been done on the operational characteristics and safety impacts of traffic operation in malfunction flashing mode. Most of the studies on flashing operations are for the low-volume night time conditions. Malfunction flashing mode can result in highly unpredictable traffic operations and every effort should be made to reduce its occurrence and duration.

In order to address the economic impact of providing an alternative power source at signalized intersections, this paper evaluated the benefits and costs of putting alternative power sources in urban arterials. A decision support tool to find the optimal investment plan of backup power was developed and demonstrated with a case study. Benefit-cost ratio is considered as decision making criteria. The benefits of the alternative power are stated as user benefits, non-user benefits and others. The primary benefit will be improving traffic operation. The alternative power systems studied in the case study includes a wind turbine and several solar panels mounted on existing traffic poles, and a battery bank. The renewable sources, if harnessed, would add advantages of cleaner energy and sale of excess production. The costs include initial investment, and operation and maintenance cost. The decision support problem can be solved using a discrete optimization model, which will identify the best installation intersections and the design combinations for each identified site. The solution will maximize the benefit-cost ratio under budget constraints. The benefit-cost analysis was conducted under the procedures recommended in the 2010 edition of *User and Non-user Benefit Analysis for Highways (the Red Book)*. The benefits of an alternative power source were estimated by the loss of operational efficiency, safety, environmental costs and other impacts if such a system was not present. The full signal operation was compared to the AWSC to find these benefits.

USER BENEFITS
The user benefits of providing alternative power sources at signalized intersection include travel time saving, vehicle operation cost saving and accident cost saving. An earlier study by the author found that dark signals at high speed intersection can result in significant delay, excessive fuel consumption and mobile emissions and loss in productivity and human resources (7). That study also described the details of the methods to estimate each type of benefits used in this paper.

**Travel Time Saving**

AWSC can provide safe and efficient traffic operation under certain traffic volume and geometric conditions (8). Program flash for late night/early morning could produce the lowest delay when the traffic volumes are low (less than 200 vehicles per hour on the major approaches) (9). However, the performance of AWSC under high volume cannot be identified from current literature. As the total intersection capacity is limited under AWSC operation (I), this operation mode can cause increases in delays at an intersections high traffic volume. In this study, the delay of AWSC operation is compared to that of the normal signal operation to get the travel time saving. The cost of delay is obtained by multiplying total system delay and the cost of travel time.

Delays under different control types can be estimated by microsimulation models. When simulation is not preferred, the empirical models can be used. The delay at a signalized intersection can be obtained from engineering study by the methodology provided by the Highway Capacity Manual 2010 (HCM 2010). However, in network-level application, it might not possible to conduct engineering study at each intersection in the network. In this case, the quick estimate method in the HCM 2010 can be used when the data of AADT are available. The average delay per vehicle at AWSC intersection can be estimated by empirical delay models with intersection volume on each direction (10). For the value of travel time, the Red Book provides the value of time module. Transportation agency would have their own criteria to estimate the value of time in local projects.

**Accident Cost saving**

The safety at a signalized intersection with moderate to high volume could be jeopardized if it is under AWSC operation. Removal of signal from late night/early morning flashing mode would have an estimated reduction of 32% in all collisions and 78% in right-angle collisions compared to the time of previous flashing operation (11). Data collected at 13 intersections under flash mode found two crashes were recorded at intersections with yellow/red flash with the third crash at a signal with red/red flash in a period of 12.75 hours; the three recorded crashes result in a crash rate of 143.5 crashes per million entering vehicles, which identified that a flashing signal may be a potentially hazardous condition for drivers (3).

A direct way to estimate the safety benefits would be to use the records of crashes during power outages. As this kind of data is rarely available, crash rate can be estimated by empirical models. The National Cooperative Highway Research Program developed procedures for predicting the Total Injury Crashes (TIC) at stop-controlled and signalized intersections with data of AADT (12). The predicted TIC includes both fatal crash and injury crash. The predictive models are in the following form:

\[
TIC = \alpha(F_1)^b(F_2)^c
\]

where, \(F_1\) is the entering AADT on a major road, \(F_2\) is the entering AADT on a minor road.

The accident cost saving can be estimated by multiplying the reduction of crashes and the unit cost of crashes. There are different evaluation systems for the cost of crashes, such as the crash costs published by the National Safety Council and the value of statistic life used by FHWA. Usually, the states have their guidelines of estimate the cost of crashes.
Operation cost saving

During the congestion caused by the inoperative intersection, vehicles spend more time on the road, which results in additional fuel consumption and vehicle emission. In this study, the operation cost saving is estimated by the saving on fuel consumption. The change in fuel costs due to delay changes can be estimated by a delay-based methodology provided by the Red Book. For a given vehicle class, the change in fuel costs due to a change in travel delay is estimated by

\[
\text{change in fuel cost} = g(D_0 - D_1)p;
\]

where \( g \) is fuel consumption in gallons per minute of delay, \( (D_0 - D_1) \) is the change in delay, and \( p \) is the price of fuel. The fuel consumption per minute of delay is given by different free flow speed and vehicle type.

NON-USER BENEFITS

Installing and operating alternative power systems at signalized intersections can alter the environment through vehicle noise and emissions, and other avenues. The non-user benefits focus on the environmental impacts of the gaseous emission reduction from the reduction in fuel consumption when an alternative power source is present during an outage.

Environmental impacts

The emission from vehicle fuel consumption can be estimated by fuel-based emission models. The method in the case study using the following formulas (13):

\[
\begin{align*}
\text{CO} &= \text{Fuel consumption (gallon)} \times 69.9 \text{ g/gallon} \\
\text{NOx} &= \text{Fuel consumption (gallon)} \times 13.6 \text{ g/gallon} \\
\text{VOCs} &= \text{Fuel consumption (gallon)} \times 16.2 \text{ g/gallon}
\end{align*}
\]

CO\(_2\) emissions are proportional to the amount of fuel consumed. CO\(_2\) emission from gasoline is 19.4 pounds per gallon and 22.2 pounds per gallon from a gallon of diesel (16).

The cost of pollutant can be estimated by the product of the amount of reduced emissions and the unit cost of the pollutant. The total environmental benefit in dollar value is the sum of costs of all the emissions. Vehicle emissions including CO, NOx, and VOCs are harmful to human health. NOx is one of the primary causes of acid rain, which damages materials and kills plant foliage. The monetary costs of air pollutants can be measured in three ways (14): 1) as the cost of cleaning up the air near the source of degradation, 2) as the cost associated with addressing the effects of degradation, and 3) as the willingness of persons to pay to avoid the degradation. Muller and Mendelsohn estimated the marginal damage cost for several kinds of pollutions (15). Table 1 shows the estimation for NOx and VOCs at the lower (25\(^{th}\) percentile), median (50\(^{th}\) percentile) and upper (75\(^{th}\) percentile) levels. The social cost of carbon (SCC) is an estimate of monetized damage cost of an incremental increase in carbon emissions in a given year. SCC assesses damages to ecosystems, freshwater resources, forests, coastal areas, human health, and industry (17). The Department of Transportation used a domestic SCC value of $2 per ton of CO\(_2\) in the final model year 2011 Corporate Average Fuel Economy (CAFE) rule.

<table>
<thead>
<tr>
<th>TABLE 1 Estimated Marginal Damage Cost of Emission ($/ton/year)</th>
</tr>
</thead>
</table>

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Secondary Impacts

The project of installing alternative power sources at signalized intersections would not affect the local land use, property values, and construction expenditures. In large project applications, the payments to employees and contractors can generate additional cycles of spending and consumption, however, this impact may not provide a significant net increase in local economic activity, so these benefits are not considered in this study.

OTHER BENEFITS

The section discusses the benefits not identified in the Red Book. These benefits are unlikely to add significant benefits beyond those accounted for by the user and non-user benefit; however, they can have significant impacts in certain situation.

Police resource saving

Police are often called to direct traffic during traffic signals power failure, which drives up the policing costs. These resources are limited and have to be diverted for traffic guidance in case of power outage. The presence of an alternative power source can prevent the intersection from dark signals, and therefore, would save the police resources.

Renewable Energy Benefits

The alternative power system used for the case study includes wind turbine and solar panels that would bring renewable energy for traffic operation. The energy production can support the traffic signals, and the excess production can be sold back to the utility grid. Wind the wind and solar resources are abundant while the local utility price is high, the renewable energy production would add significant benefits. The benefits from green energy include the wind and solar energy production and the emission saving by generating electricity from renewable sources instead of generating form fossil fuels.

The wind energy production can be estimated by the bin Method with wind data and a turbine power curve (18). There are many software and on-line tools to predict the solar energy production, such as the PVWatts by the national renewable energy laboratory.

To estimate the emission saving from renewable energy, the net electricity generated from fossil fuels and the total pollutants from conventional power plants were obtained from U.S. Energy Information Administration (EIA) statistics (19). The emission of air pollutants per kWh generated was estimated from these statistics, as shown in Table 2. Knowing the renewable energy production and the unit cost of pollutants, we can estimate monetary benefits from green energy.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Lower marginal damage cost</th>
<th>Median marginal damage cost</th>
<th>Upper marginal damage cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>180</td>
<td>25</td>
<td>370</td>
</tr>
<tr>
<td>VOCs</td>
<td>120</td>
<td>180</td>
<td>280</td>
</tr>
<tr>
<td>SO₂</td>
<td>550</td>
<td>970</td>
<td>1,300</td>
</tr>
</tbody>
</table>

**TABLE 2 Emissions Saving from Renewable Energy**

<table>
<thead>
<tr>
<th>Total emission (thousand metric tons)</th>
<th>CO₂</th>
<th>SO₂</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2,269,508</td>
<td>5,970</td>
<td>2,395</td>
</tr>
</tbody>
</table>

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| Net generation (thousand megawatt hours) | 2,726,452 |
| Emission rate (ton/kWh)                | 8.32 E-04 | 2.19 E-06 | 8.78 E-07 |

**BENEFIT-COST ANALYSIS**

The traffic operation agencies often face a problem of improving traffic performance with limit budget. To stream the investment to the most beneficial project on alternative power sources, a tool to support decision-making was developed to identify the installing sites and system configuration at each identified site. The benefit-cost ratio is used as the decision making criteria. The project benefits include user benefit and non-user benefit from signal power backup, and other benefits secondary benefits brought by the alternative power source. The project cost represents the budgetary cost to the transportation agency. The project costs include the costs associated with developing the project, the cost of Operating and Maintenance (O&M), and the financing costs that must be borne to assemble the financing for the project. The benefits and costs stated in dollar values should be discounted to the present value as the project provide benefits and impose costs over time. An optimal plan would maximize the benefit-cost ratio of the whole project. The optimal investment planning problem can be formulated as a discrete optimization problem to identify the installation location and the design combinations for each identified location.

The general formulation can be stated as follows:

Minimize $r = \frac{\text{project life-cycle benefits}}{\text{project life-cycle costs}}$

Subject to budget constrain

where,

- life-cycle benefits = user benefits + nonuser benefits + other benefits
- life-cycle costs = initial investment + O&M costs + financing costs

**CASE STUDY**

The case study was conducted in the city of Kearney in Nebraska. Six intersections along the 2nd Avenue (20,050 feet) and 25th Street (15,955 feet) were considered to install the alternative power systems. The six intersections are located in the main corridors. The topology of the six sites is shown in Figure 1. Site one to 4 are part of U.S. highway 30. The segment between site three to four is part of Nebraska highway 10 and the segment between site three to site six is part of the Nebraska highway 44. Site three is the busiest intersection among the six, with peak hour volume of 3,700 vehicles entering the intersection. Site six near the ramp to interstate 80, traffic during peak hours is 1,800 vehicles per hour. The alternative power system has four types of design configurations: (i) battery backup system; (ii) a wind turbine and battery bank system; (iii) one or two solar panels and battery bank system; and (iv) a wind turbine, one or two solar panels and battery bank systems. The battery bank has four 120VAC 305Ah batteries, which is designed to supply the signals for two hours of full operation at 700 watt load and another 4 hours of flashing operation at 350 watt load. The system can also provide steady power when the line power is not qualified. The 1.0 kW wind turbine and 210 watt solar panels would be mounted on the traffic signal poles at the intersection, and the battery bank and control system would be enclosed in in a cabinet attaching to the traffic cabinet. The benefits of the proposed alternative power system include the benefit as backup power during power outages and the benefit from renewable energy. The benefits as backup power is compose of the use benefit, non-user benefit, and police resource saving. Before the benefit-cost analysis, field studies were conducted to check the physical feasibility of mounting the proposed alternative power system on existing infrastructure (7). Among the six potential project sites, only two (site 1 and 5) of them were suitable for wind turbine.
Power Backup Benefit

The primary benefit from an alternative power source is the potential benefits associated with power backup during an outage. This kind of benefits can be seen as the benefit from the battery bank. To study the power outage and interruption history at the six intersections, the UPS event records between April 2011 and April 2012 were retrieved from the UPS devices at these intersections. The period when an outage occurred or the line power is not qualified was considered as line power unavailable time. As the traffic condition vary by time of day, the line power unavailable time was studied by the traffic peak periods. Four analysis periods were identified: a.m. peak (7:00-9:00), noon peak (11:00-13:00), p.m. peak (16:00-18:00), and off-peak period. The distribution by time of day for the power unavailable periods is shown in Figure 2. These time periods corresponded to the duration having same signal timing plan as obtained from the city. The data of annual average outage per custom in the utility grid were obtained from local utility services. The duration of outage at each intersection was distributed to different time of day following the distribution of line power unavailable time. The distributed outage duration is critical as the travel time saving and fuel consumption were estimated based on it.

FIGURE 2 Power unavailable time frequency by time of day.

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At the time of analysis, only the AADT data and peak period volumes of all the approaches at each intersection were available. The 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 (10). The mean hourly income of $17.05 per hour for the studied area was used as the value of travel time. With the estimated delays, the extra fuel consumption during AWSC operation was estimated by the delay-based fuel consumption model (6). The emissions from fuel consumption were then calculated from the fuel-based emission model (13, 16). In this paper, the CO₂ emissions from gasoline (19.4 pounds/gallon) are used as the conservative CO₂ emission rate for all types of fuel. The domestic SCC value of $2 per ton in the final model year 2011 CAFÉ rule was used as the price of CO₂. The Midwest district average gasoline price for all grades in 2011 was used as the fuel price (20). The median marginal damage costs in Table 1 are chosen as the unit cost of additional emissions during power outages. For the saving in police resource, the police traffic directing time was supposed to be equal to the outage duration, and the mean hourly income was also used as the unit cost of police directing.

For the accident cost saving, the TIC models were used to predict the crash rate under both signal control and AWSC operation (12), as no field data were available. The ratio of fatal and injury crash to the total crash was calculated using local crash statistics from Nebraska Office of Highway Safety, which is used to estimate total crash rate with the outputs of TIC models. The crash cost data were also obtained to estimate the saving of reducing one crash (22).

<table>
<thead>
<tr>
<th>Type of Crash</th>
<th>Number of Each Type of Crash</th>
<th>Cost per Each Type of Crash</th>
<th>Total Cost of All Types of Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>8</td>
<td>$1,410,000</td>
<td>$11,280,000</td>
</tr>
<tr>
<td>Injury</td>
<td>268</td>
<td>$70,200</td>
<td>$18,813,600</td>
</tr>
<tr>
<td>Property-Damage Crash</td>
<td>636</td>
<td>$8,900</td>
<td>$5,660,400</td>
</tr>
<tr>
<td>Total</td>
<td>912</td>
<td>-</td>
<td>$35,754,000</td>
</tr>
<tr>
<td>Average Saving of Reducing One Crash</td>
<td>$35,754,000/912 = $39,203.95</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The potential benefits of providing a power backup at each site under existing traffic condition are shown in Figure 2. The benefits are more favorable at intersections with high volumes. The benefits at each site in each analysis year were estimated, and the life-cycle benefits from power backup at a specific site can be estimated by the following equation:

$$\text{life-cycle power backup benefit at site } i = \sum_{j=1}^{15} b_{i,j}$$

where $b_{i,j}$ is the power backup benefit at site $i$ in the $j$th year of the 15-year life-cycle.

The life-cycle benefit was calculated for each site. Figure 3 shows the first-year potential power backup benefits at the studied sites, while Figure 4 shows the average benefits for the entire intersection network for the first project year, assuming each intersection have any type of alternative power source. It should be noticed that the dynamic traffic interactions between interactions are not considered. When an outage occurs at one site, it would cause degraded traffic operation at upstream and downstream intersections, but this impacts were not estimated in this study.
FIGURE 3 Potential power backup benefits at the potential sites at the first project year.

FIGURE 4 First-year average power backup benefit per hour of outage at all sites.

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Renewable Energy Benefit

If wind or solar energy generating system is installed, the benefits from renewable energy can be estimated as:

$$\text{lifecycle renewable energy benefit at site } i = \sum_{j=1}^{15} (e_{i,j} p_j + e_{CO_2,j} p_{CO_2,j} + e_{SO_2,j} p_{SO_2,j} + e_{VOCs,j} p_{VOCs,j})$$

where, $e_{i,j}$ is the renewable energy benefit ($) at site $i$ in the $j^{th}$ year of the 15-year life-cycle, and it can be wind or solar energy; $p_j$ is the price of electricity at the $j^{th}$ year; $e_{CO_2,j}$, $e_{SO_2,j}$, and $e_{VOCs,j}$ are the amount of air pollutants saved from renewable energy source; and $p_{CO_2,j}$, $p_{SO_2,j}$, and $p_{VOCs,j}$ are the prices of air pollutants at the $j^{th}$ year.

As there was no roadway weather station available to obtain the data for each intersection, the five-year wind and solar radiation data were collected from a weather station near site 2. The wind data were corrected to eliminate the effect of elevation differences. Using the bin method (18), the potential wind energy production is estimated to be 113 kWh per month at site 1 and 91 kWh per month at site 4. The solar radiations were assumed to be the same at each site because that the variation of solar radiation is minimal in the small the project area. The solar energy production of one panel is 375 kWh per month estimated by the PVWatts (21). The emission saving from renewable energy can be estimated with the energy production and the emission rate in Table 2. The price of air pollutants were determined by the median marginal damage costs in Table 1.

Benefit-cost Analysis

The project benefits include the power backup benefits and renewable benefits estimated above. The project cost includes the installed cost of the system components and maintenance costs. The installed cost of one unit of battery system, wind turbine system, and solar panel system are $2,852, $2,578, and $600 respectively. As the proposed alternative power system term was designed to be low-maintenance, the maintenance cost was assumed to be 5% of total system installed cost. As the local traffic operation agency would operate the power system, the operation cost was assumed to be zero. No financing cost was associated as the payment would be paid by a lump.

The decision-making support tool was developed to search for the optimal investment plan by solving a discrete optimization problem in the intersection network with six nodes and seven links. The decision variable was a $1 \times 18$ vector $X$ whose elements indicate the number of unit of battery bank, wind turbine and solar panel at the six sites. The project benefit-cost ratio, $r$, would reach the maximum by the solution of $X$. The variables and subscripts used in model formulation are listed below:

- $i$ = subscript for potential sites, $i = 1, \ldots, 6$;
- $j$ = subscript for analysis years, $i = 1, \ldots, 15$;
- $b_i$ = potential life-cycle power backup benefit at site $i$;
- $e_{w,i}$ = potential life-cycle wind energy benefit at site $i$;
- $e_{s,i}$ = potential life-cycle solar energy benefit from one solar panel at site $i$;
- $c_b$ = installed cost of a battery back;
- $c_b$ = installed cost of a pole-mounted wind turbine system;
- $c_b$ = installed cost of one unit of solar panel power;
- $X$ = integer variables indicating the number of battery bank, wind turbine and solar panels on each site;
- $Z$ = binary integer variables indicating the number of battery system, wind turbine and solar panels on each site;
The total benefit and cost of the project in a 15-year life-cycle were estimated as the following:

\[
\text{Project life} - \text{cycle benefit} = XB \\
\text{Project life} - \text{cycle cost} = XC
\]

Where, \(B_{18 \times 1} = [b_1 \; e_{w,1} \; e_{s,1} \; \cdots \; \cdots \; b_6 \; e_{w,6} \; e_{s,6}]^T\),

\(C_{18 \times 1} = (1 + 5\%)[c_b \; c_w \; c_s \; \cdots \; \cdots \; c_b \; c_w \; c_s]^T\)

Here, the present discounted value of benefits and costs were calculated by a discount rate of 3 percent as recommended by the Red book the benefits and costs measured in constant dollars. From the design configurations, the battery bank must be invested if a wind turbine or solar panel is selected. The objective function is in the following basic form:

\[
\max_X r = r(X) = \frac{XB}{XC}
\]

subject to

\[
X \cdot \left( \frac{C}{1.05} \right) \leq \text{initial investment budget},
\]

\[
x_{3i-1} - x_{3i-2} \geq 0, x_{3i} - x_{3i-2} \geq 0, i = 1, 2, \ldots, 6
\]

From the design configuration of the alternative power source, at most one battery bank, one wind turbine and two solar panels can be installed at a potential site. Moreover, the filed studies have identified that only site 1 and site 5 can be a feasible site for pole-mounted wind turbine. So, the discrete optimization model can be modified into a problem of binary integer programming. The number of solar panels at each site can be represented by the sum of two binary integer variables. The decision variable, \(X_{1 \times 18}\), is then converted to a binary vector, \(Z_{1 \times 20}\), whose elements indicate the number of battery bank, wind generator, and every unit of solar panel at the site 1 to site 6. The objective function is in the following modified form:

\[
\max_Z r = r(Z) = \frac{ZD}{ZE}
\]

subject to

\[
Z \cdot \left( \frac{E}{1.05} \right) \leq \text{initial investment budget}
\]

\[
z_2 - z_1 \geq 0, \quad z_3 - z_1 \geq 0, \quad z_4 - z_1 \geq 0, z_{3i} - x_{3i-2} \geq 0, i = 2, 3, 4, 5
\]

\[
z_{16} - z_{14} \geq 0, \quad z_{17} - z_{14} \geq 0, \quad z_{19} - z_{18} \geq 0, z_{20} - x_{18} \geq 0
\]

Where, \(D_{20 \times 1} = [b_1 \; e_{w,1} \; e_{s,1} \; b_2 \; e_{s,2} \; e_{s,2} \; \cdots \; \cdots \; b_5 \; e_{w,5} \; e_{s,5} \; b_6 \; e_{w,6} \; e_{s,6}]^T\),

\(C_{20 \times 1} = (1 + 5\%)[c_b \; c_w \; c_s \; c_b \; c_s \; c_s \; \cdots \; \cdots \; c_b \; c_w \; c_s \; c_s \; c_s]^T\)

As the number of potential site is small, this binary integer programming problem can be solved by some prevalent solvers. In this case study, the problem was solved by matlab. With the budget limit of $10,000 initial investment, the solution is given in Table 4. Site 1, 5, and 6 do not deserve any backup system. Site 3 and 4 were selected as battery and solar systems, while battery system was selected for site 2. The pole-mounted wind turbine is not economically viable as the benefits at site 1 and 5 are lower. At the high-benefit sites, like site 3, the physical feasibility check for wind turbine was failed. Compared to the wind turbine that has limit application in urban area, the solar panels can be used on most of transportation infrasres.

### TABLE 2 Optimal investment plan and design configuration for the studied sites

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CONCLUSION

The renewable energy was not a significant benefits compared to the benefits from traffic operation improvement. However, if the project site located in high wind class area and the traffic operating agency’s electricity expenditure is also high because of high utility price or large consumption, the renewable energy would have significant impacts. The areas with frequent power interruptions would result in higher benefits to cost ratio, too. When the power outage duration is beyond the designed backup hours of the battery bank, the on-site renewable energy, if available, can keep charging the battery and supply the traffic signals.

The benefits estimated in the case study are consecutive. The impacts of interaction between intersections were not considered. As a power outage is a random event, it can be happen at any time of day. During an outage occurred in peak traffic hours, the alternative power source would induce more benefits than that induced during outages in off-peak, assuming the duration are the same. Usually, the dark signals or malfunction flashing signals due to power interruption cannot be revert to full operation immediately after the grid power is available. It would take some time for the operating staff to reach the intersection and fix the problem. The operating agencies usually have no monitor system to identify a signals reverting to malfunction flashing due to line power interruption, which usually rely on the citizen reporting. Studies have found the average time to response to a malfunction signal is about three hours (2). The designed alternative sources are able to support the signals for more than three hours. These benefits are not included in the model used for the case study.

The tool developed in this paper can be used for both investment planning and prioritizing project sites when budget is limited. The model works well if the user has reference for the power outage history. But it is also flexible for the user’s to conduct a sensitivity analysis by setting preferred outage duration and traffic volume data. The optimization technology used in the case study is easy to solve. In case of large-scale network applications, the formulation can be modified to meet the requirements for user-preferred optimization algorithm.

The alternative power sources at signalized intersection can improve the traffic operation reliability and protect the traffic controllers from electrical surges. Systems with renewable energy generating capacity can bring revenue for the operation agency. As only a few literatures have been done associated with dark signals, and the records on intersection power interruption are rarely available, this paper provides provide a tool for the transportation agencies to plan for alternative power sources at isolated intersection or intersection network. Local agencies with similar traffic conditions can directly use the results in this paper as a reference. Our future study will use simulation technology to model the economic impacts in large-scale network and improve the model to fit different level of applications.

REFERENCES


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