NIST Technical Note 2013

Improving the Economic Viability of Investment in Building Sustainability through the Valuation of Resilience-based Co-Benefits

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Abstract

In recent years, building designers and community planners have recognized the importance of taking an integrated approach to sustainability and resilience, but in practical application this dual objective approach is not often intentionally realized. For some time, the two efforts have been largely disconnected despite overlapping agendas and shared co-benefits. A building cannot be classified as sustainable if it is not durable enough to withstand the impacts of natural disasters and maintain its functional resilience. Therefore, formally integrating the two concepts is important to ensure the development of long-term sustainable residential and commercial buildings that can withstand the increasing large-scale disaster events of greater magnitude than ever before. A common deterrent for many homeowners to invest in sustainable building elements are the significant upfront costs required. However, the economic viability of such investments can be improved if homeowners facing hazard events or stressors see their investments in sustainability as a way to increase the resilience of their homes to disasters, benefiting from the monetization of numerous direct and/or indirect cost savings or losses avoided. A case study based on a single-family home in Maryland with an installed rooftop solar photovoltaic (PV) system with the option for additional battery storage is used to reveal the potential effects of considering resilience benefits in economic analyses of investments in residential sustainability. The results of an environmental impact assessment are then used to reveal underlying tradeoffs between investments in building sustainability (indirect resilience) and a building's environmental footprint.

Key words

Building economics; community; hazards; planning; recovery; resilience; hazards; residential; resilience planning; renewable energy

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Glossary

CAIDI	Consumer Average Interruption Duration Index
CUE	cost per unserved electricity
DRR	Disaster Risk Reduction
E+	EnergyPlus
ICE	Interruption Cost Estimate
IOPO	immediate occupancy performance objectives
LCA	life-cycle assessment
LCC	life cycle costing
LCIA	life-cycle impact assessment
LEED	Leadership in Energy and Environmental Design
NCEI	National Centers for Environmental Information
NMC	nickel manganese cobalt
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NZERTF	Net-Zero Energy Residential Test Facility
NZ-PV	Net-Zero Photovoltaic
PV	photovoltaic
TOU	Time-of-use
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SAM	System Advisor Model
USGBC	US Green Building Council
WCDRR	World Conference on Disaster Risk Reduction

1. Introduction

1.1. Sustainable Buildings and Infrastructure

Sustainable development as a streamlined effort gained momentum with the 1992 Rio Earth Summit where internationally the definition of “meeting the need of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission 1987) was widely accepted. By the 2002 Johannesburg Earth Summit, the initial intent of environmental and socioeconomic progress had given way to increased debate over inherent conflicts between sustainability and economic development. Adoption of the Sustainable Development Goals in 2015 brought together the goals of addressing long-term stressors across systems that together constitute communities (e.g., social, economic, natural environment, built environment) (UN 2017).

On the single building level, which constitutes a complex system in and of itself, the Leadership in Energy and Environmental Design (LEED) Green Building Rating System began in 2000 (Vierra 2016). Sustainable buildings – both commercial and residential – continue to be evaluated for sustainability by green building benchmarks established through building industry stakeholders. Additionally, there is value in a systemic objective evaluation process for buildings—that can be applied to any building—that considers both the economic and environmental valuation over a given time horizon.

Almost a decade ago, the Applied Economics Office (AEO) at the National Institute of Standards and Technology (NIST) first proposed an approach to systematically assess the “returns” on sustainable building design that considers simultaneously: 1. environmental performance through life-cycle assessment (LCA) and 2. economic performance through life cycle costing (LCC) (Helgeson and Lippiatt 2009). Since this time, NIST has built a Net-Zero Energy Residential Test Facility (NZERTF) and systematically modeled LCC and LCA valuation verified through measured experimental data from the NZERTF (Healy, Kneifel, and O'Rear 2018, Kneifel, O'Rear, and Webb 2016).[1]

1.2. Resilient Buildings and Infrastructure

Measuring resiliency has become a priority in recent years due to the increasing cost of losses from disasters. World-wide losses from disaster events is estimated to have been $306 billion in 2017 (SwissRe 2018). The National Centers for Environmental Information (NCEI) within the National Oceanic and Atmospheric Administration (NOAA) estimates that there have been 218 natural weather disaster events, each resulting in at least $1 billion in damage and economic losses in the U.S. from 1970 to October 2017 (American Society of Civil Engineers (ASCE) 2016, 2014).

A number of international governments adopted a framework on Disaster Risk Reduction (DRR) at the third UN World Conference on Disaster Risk Reduction (WCDRR) in Sendai, Japan, in March 2015 (UN 2017). Resilience planning is increasingly performed at a community scale, as it relates to a sociotechnical system of systems – infrastructure, economic, and social systems (Laracy 2007, McAllister 2015, Gilbert et al. 2015). Though full and sustained functionality of individual buildings is dependent upon systemic factors (e.g., power grid), there is value in addressing increasing resilience at the building level,

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[1] The analysis presented in this paper is based upon a case study developed specific to the NZERTF.

based on the role of the building in a community. The US Green Building Council (USGBC) has made resilience a policy priority (Larsen et al. 2011) and increasingly communities are trying to incorporate resilience into their local building codes (Bloomberg 2013).

Presidential Policy Directive 8 (PPD-8 2011) defines resilience as "the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies" and Presidential Policy Directive 21 (PPD-21 2013) on Critical Infrastructure Security and Resilience expands the definition to include the "ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions." In 2017, the U.S. Senate Committee on Appropriations directed NIST to create a comprehensive research plan for developing immediate occupancy performance objectives (IOPO) for commercial and residential buildings (U.S. Senate Committee on Appropriations (114th Congress) 2016). Developing IOPO for building functionality is a subset of generally increased infrastructure resilience to chronic stressors and acute shocks and is recognized as important for improving national resilience. To support these other developments, including resilience improvements in a manner that allows them to be visible in the economic analyses for building economics is a key step forward.

1.3. Integrating Sustainability and Resilience Objectives

In recent years, building designers and community planners have recognized the importance of taking an integrated approach to sustainability and resilience, but in practical application this dual objective approach is not often intentionally realized. For some time, the two efforts have been largely disconnected despite overlapping agendas and shared co-benefits. There are numerous direct or indirect costs savings or losses avoided that can be monetized and applied to the economic analysis of an infrastructure plan.

In thinking about resilience planning, the *resilience dividend* has been highlighted by Fung and Helgeson (2017) as "the net benefits from investing in enhanced resilience in the absence of a disruptive event...which captures the intentional or unintentional pursuit of multiple objectives, and the possibility of creating externalities in the process." Under this definition, planning for resilience can have co-benefits that address sustainability goals and vice versa (i.e., resilience co-benefits that arise from sustainability planning).

In a detailed review of the literature, Marchese et al. (2018) find that there are three general management frameworks for organizing resilience and sustainability objectives: (1) resilience as a component of sustainability, (2) sustainability as a component of resilience, and (3) resilience and sustainability as separate objectives. This paper looks at a specific case of the third category, namely resilience and sustainability as concept with separate objectives that can complement (or compete) with each other; this type of approach is like that taken by Bocchini et al. (2013).[2]

It is likely that residential and commercial building owners interested in sustainable elements – new or retrofit – would also be open to elements that boost resilience capacity. Conversely, it is possible that homeowners facing hazard events or stressors may opt for sustainable building elements that also increase the resilience of their homes to disasters. This is an argument that applies across various building components and structural elements, but this paper focuses on solar-plus-storage for a residential home as an initial case study.

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[2] Bocchini et al. (2013) looks at commercial sector and resilience is treated as a structural performance indicator that accounts for structural performance and recovery patterns under extreme events.

The impact of valuing resilience in the economic analysis of solar-plus-storage for commercial systems is beginning to be analyzed (Laws et al. 2018). Yet, it is still the case that the *resilience benefit* of solar-plus-storage is typically not included, since the exact value of resilience can be subjective. This topic is discussed in greater detail in Section 2.3. Furthermore, in the residential context, there tends to be relatively lower cost to electricity ($/kWh) due to rate structures in comparison to commercial rates (Sullivan, Schellenberg, and Blundell 2015). But including the value of resilience can be useful in making a more compelling business case for solar-plus-storage.

2. Research Methodology

2.1. Research Objectives and Hypothesis

The aim of this paper is to highlight the impacts of considering resilience benefits in economic analyses of residential sustainability investments. A case study based on a single-family home in Maryland with an installed rooftop solar photovoltaic (PV) system with the option for additional battery storage is used to address this question. It is hypothesized that application of a traditional LCC economic framework, as discussed in the following section, will show that investment in solar PV with battery storage will not be economical; however, accounting for potential avoided damages and losses from avoided grid outages can improve the economics of the investment considerably.

2.2. Economic framework for evaluating investment in sustainability

LCC analysis is a popular economic approach to project evaluation. It accounts for all costs related to the development, owning, operating, maintenance, and repair (OM&R), and end of life for a project. LCC analysis has been applied extensively to buildings in the evaluation of building design alternatives satisfying some required standard of building performance – often requiring differing levels of upfront investment costs, OM&R costs, costs of disposal, and different project lifetimes (Fuller and Petersen 1996). [3] Generally, LCC analysis is a useful tool in evaluating the long-term cost-effectiveness of various energy conservation projects based on the tradeoffs between higher initial investment costs and reduced expected future costs associated with a project's operation.

Total LCC is calculated by summing over all costs (C_t) realized in each year (t) of the study period (N), which are discounted to present value dollars using discount rate (d) (see equation 1).

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \qquad (1)$$

The costs considered are the initial capital (i.e. construction costs), capital replacement costs, energy-related operating costs, non-energy-related OM&R costs, and the residual value (treated as a negative cost). The residual value refers to remaining value of a building and its components at the end of a designated study period or a building's lifetime. In the case of evaluating alternative building designs with characteristically different features, the building design with the lowest LCC is the more cost-effective alternative.

The above LCC formula is consistent with the LCC methodology defined by the suite of ASTM Building Economic Standards (ASTM 2012) and NIST Handbook 135 (Fuller and Petersen 1996) and used in standard evaluations of buildings-related energy conservation projects. The formula, however, does not explicitly account for any future damages or losses linked to both anticipated and unanticipated hazards and disruptions. This can be remedied by including estimates of potential future damages and losses within the LCC framework (Equation [2]):

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[3] Requirements include acceptable levels of occupant comfort, safety, adherence to building codes and engineering standards, system reliability, etc. (Fuller and Petersen 1996).

$$LCC = \sum_{t=0}^{N} \frac{(C_t + DL_t)}{(1+d)^t} \qquad (2)$$

where the DL_t cost component is the expected (future) damages and losses. In the case of evaluating resilient buildings, a measure of avoided damages and losses (i.e., the extent to which project investments in resilience can reduce expected future damages and losses) can be approximated by taking the difference in damages and losses with and without the investment in resilience. [4]

2.3. Valuing resilience: direct and indirect values of avoided losses

Valuing avoided losses due to increased resilience is generally difficult because the value of energy-not-supplied arises from two cost/value components. First, direct costs arise from damages that lead to a loss of value and can be directly related to household expenses (e.g., cost to replace spoiled food). Second, indirect costs result from a loss of opportunity (e.g., not being able to do work or loss of leisure time). Indirect costs depend largely on customer factors such as the needs for uninterrupted supply, which varies according to personal needs, existing assets, and individual preferences (Praktiknjo, Hähnel, and Erdmann 2011). There are four major ways by which avoided losses – also noted as cost per unserved kWh—is valued in economic terms: (1) Direct surveys/interviews (Reichl, Schmidthaler, and Schneider 2013); (2) Production-function approach; (3) Revealed preferences through market behavior (Sanghvi 1982, Deubel 2013); (4) Case study analysis.

As noted by Shivakumar et al. (2017), the range of identified cost per unserved kWh is highly variable; in their review of studies in the EU-28 the cost per unserved kWh ranged from 3.2 EUR ($3.84) to 15.80 EUR ($18.98)[5]. In addition to variation in data collection and analysis, this variation in values for uninterrupted electricity is largely explained by the fact that blackout damages (direct and indirect) fall into two categories: (1) circumstances of the blackout and the perceived frequency of blackouts and (2) consumer factors related to the role and importance of uninterrupted supply.

2.4. Additional analysis – environmental impacts

Life-cycle assessment (LCA) is a tool used by practitioners in the building community to assess the environmental footprints of buildings. LCA takes a cradle-to-grave systems approach for evaluating environmental impacts based on an accounting of the inputs and outputs associated with a product's life-cycle (Blanchard and Reppe 1998, Fouquet et al. 2015, Anand and Amor 2017). This study uses LCA inventory data in conjunction with input-output (I-O) data in a hybrid life-cycle impact assessment (LCIA) framework to quantify the whole-building environmental impacts of the alternative building designs

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[4] In some examples of resilience there are benefits of improved performance over time, opposed to at the point of a disruptive shock, that should be captured.

[5] All values adjusted to 2017 USD.

considered in this study. Each environmental impact is linked to one of twelve impact categories.[6,7]

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[6] The twelve categories are: (1) primary energy consumption (kBTU), (2) global climate change potential (kg CO_2e), (3) human health – criteria air pollutants (kg PM10 eq), (4) human health – cancer effects (CTUh), (5) human health – non-cancer effects (CTUh), (6) water consumption (kg), (7) ecological toxicity (CTUe), (8) eutrophication potential (kg N eq), (9) land use (Acre), (10) smog formation (kg O_3 eq), (11) acidification potential (mol H+ eq), and (12) ozone depletion (kg CFC-11 eq).

[7] For additional information on these impact categories, the hybrid LCIA framework, and the LCA data sources used in this study, please refer to Kneifel et al. (2018).

3. Case Study – Implementation of Economic Framework

Power outages can be a serious issue for modern societies; as Praktinkjo et al. (2017) point out "when examining the needs of human beings Maslow's hierarchy, many of those basic needs are dependent on electricity." Furthermore, during a sustained outage that results from a disruptive event, access to refueling for generators may become highly limited, while battery storage may prove a successful on-site temporary solution.[8] Power outages are a nuisance for everyone, but, for those dependent on medical devices, such as respirators, or medications requiring refrigeration, access to electricity can become a life-threatening matter. The example discussed in this paper is largely disaster-type agnostic – the motivating event may be wind, snow, or human error – and we are interested in the fact that blackouts are the end outcome of a disturbance event.

3.1. Simulating Household Operating Energy Consumption using EnergyPlus

The NIST NZERTF serves as a "test bed" demonstrating the realities of a net-zero energy single-family house having the "look and feel" of a typical residential home constructed in Maryland.[9] The LEED Platinum, single-family home is located on the NIST campus in Gaithersburg and operates with a simulated family of four living virtually in the house and includes numerous energy-efficient technologies and a 10.2 kW rooftop solar photovoltaic (PV) system (no additional energy storage systems). The programmed daily activities of the simulated family are based on user profiles developed by the Department of Energy's Building America Program. The house faces true south and has two stories of living area (2713 ft^2 [252 m^2]), with four bedrooms and a fully-conditioned basement (1453 ft^2 [135 m^2]) and is roughly 60 % more energy-efficient (with the inclusion of rooftop PV) than a newly constructed home in the same area compliant with the most recent adopted series of residential building energy codes.

This case study used a simulated model of the NZERTF developed in version 8.8.0 of Department of Energy's EnergyPlus (E+) whole-building energy simulation software tool, which estimates the annual operating energy performance for a given building design based on hourly data solar radiation data and meteorological inputs characteristic of weather conditions for a specific location.[10] The NZERTF simulation model was constructed in E+ according to the building specifications listed in Kneifel and O'Rear (2015). The NIST NZERTF was selected for this analysis because the E+ NZERTF design has been previously validated using measured in situ performance data–therefore it is useful in testing a variety of hypothetical scenarios related to the performance of its many systems.

3.2. Simulating Household PV Production with/without Battery Storage using SAM

The National Renewable Energy Laboratory's System Advisor Model (SAM) is used to predict annual PV production levels and the impacts of battery storage on household grid-

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[8] Of course, there is still limits to the time the battery can support household functions. And damage to PV from a storm etc. and the battery from flooding could be an issue.

[9] For additional information refer to Fanney (2016).

[10] The typical meteorological year 3 (TMY3) weather file used is for Washington DC Dulles International Airport from the National Solar Radiation Database.

based electricity demands because of its high level of detail related to the performance models for both the PV and the battery storage capabilities (National Renewable Energy Laboratory (NREL) 2018). The hourly energy load profile generated by the E+ NZERTF simulation is used in SAM to capture the potential for reducing residential electricity peak demands using battery storage. Measures of annual operating energy use in this study are based on calculations of net energy consumption using SAM model outputs for annual solar PV production and grid-based electricity consumption accounting for battery storage use. A similar TMY3 weather file for Washington DC Dulles International Airport is used in SAM to capture the local weather conditions for Gaithersburg, MD and their impact on PV generation.

The current NZERTF rooftop PV system setup includes four rows of eight SunPower SPR-E10-320 modules with two SunPower SPR-5000x (240V) inverters. Solar PV modules of the same specifications and manufacturer were selected in SAM. Yet, only a single 10 kW SolarEdge (SE10000A-US [240V]) inverter was chosen to ensure compatibility with the battery type discussed in the next section and to remain consistent with typical DC-coupled system setups.

The brand of battery modeled in SAM is a LG Chem 9.8 kWh lithium-ion nickel manganese cobalt (NMC) battery. Unlike the typical lead-acid batteries, lithium-ion NMC batteries tend to be more expensive but often require fewer replacements over the lifetime of a system. The LG Chem brand of battery was selected based on the recommendations of local Maryland residential energy storage installers. The battery bank capacity was determined using the *SolarResilient* solar PV and battery storage system sizing tool, which allows users to approximate the required size of their resilient solar system to withstand extended periods of wide-scale grid outages (Arup 2018). Based on the tool calculations, two LG Chem batteries would be required to support the emergency electrical loads of the NZERTF.[11,12,13]

With a usable capacity of 9.3 kWh, it is assumed that the entire usable capacity can be cycled daily within a minimum state of charge of 30 % and a maximum state of charge of 100 % .[14] Given the lack of publicly available data on battery lifetime cycling information for the LG Chem battery, we rely on SAM's default values, while assuming the battery bank is replaced once a 70 % threshold capacity is reached.[15] SAM calculations indicate that replacement will occur every 15 years given the 70 % threshold.

Residential electricity rates imposed by Potomac Electric Power Company (Pepco) in the state of Maryland are flat-rate charges offering alternative pricing schedules for winter (Oct.-May) and summer (Jun.-Sept.) The "Peak shaving: 1-day look ahead" battery dispatch

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[11] Two of the required inputs for the sizing tool are hourly load data and a desired emergency load percentage. Results from the E+ simulation of the NZERTF were used to provide hourly load data inputs. The emergency load percentage selected for this analysis was 70 % to ensure that the heating, ventilation, and air-conditioning (HVAC) system could continue to operate during an extended grid outage along with other important, less energy-intensive loads at a probability greater than 50%.

[12] The assumed critical loads are associated with the refrigerator, adjusted operation of the air-source heat pump, heat recover ventilator, a single cell phone charger, and adjusted use of the indoor lighting fixtures. Critical loads total 19.8 kwh/day.

[13] For additional product information on the LG Chem battery see https://www.civicsolar.com/product/lg-chem-98kwh-63ah-400v-lithium-ion-battery-resu10h.

[14] Charge limit are based on assumed minimum and maximum state of charge limits in DiOrio, Dobos et al. (2015) for lithium-ion NMC batteries.

[15] The current warranty for the LG CHEM RESU10H states the battery must retain at least 60 % of it nominal energy (9.8 kWh) for either the 10 years after initial date of installation or for a minimum "Energy Throughput" of 24.3 MWh to be covered by the warranty. The 70 % threshold was chosen to capture a more likely replacement timeframe (15 years) than a SAM calculated lifetime of 20 years given a 60 % threshold.

model option in SAM was selected due to the absence of an incentive-type electricity pricing structure such as time-of-use (TOU) pricing.[16]

3.3. Economic Analysis

Performing the LCC-based economic analysis requires the specification of all parameters impacting the value of installing rooftop solar PV with and without battery storage. Majority of the system component costs listed in Table 1 are based on vendor quotes. Other non-component costs are based on values used in other financial analyses of residential solar PV systems.[17]

Table 1. PV/battery system costs and parameters

Parameter	Units	Value
Cost of PV Module[18]	2018$/Wdc	2.46
PV Capacity	kW	10.2
Cost of Inverter	2018$	2487
Cost of Battery	2018$	5650
Cost of Critical Load Subpanel[19]	2018$	200
Cost of Maintenance	2018$/year	19
Installation Cost Markup	%	15
Profit/Overhead Markup	%	20
PV Degradation	%/year	0.50
Real Decline in Inverter Costs	%/year	4
Real Decline in Battery Costs	%/year	4
Replacement – Modules[20]	Years	35
Replacement – Inverter	Years	12
Replacement – Battery	Years	15

Table 2 lists all the necessary parameters for computing the LCC for each scenario. The annual energy consumption and PV production values are based on simulation outputs of E+ and SAM models, respectively. Both the electricity consumption rates and net metering charges are based on 2018 charges to Maryland Pepco residential customers, where the consumption rate is an average of the seasonal consumption rates (Pepco 2018). The federal investment tax credit (ITC) for residential solar energy systems will no longer be available in year 2022 – therefore, it is assumed that the credit (30 %) will only be available in the initial year of installation.[21] Two financing options are considered in this analysis: (1) a full upfront

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[16] The “Peak-shaving: 1-day look ahead” option assumes that for each day, the battery will be charged based on the next day’s solar resource and load data, and operate the system in a manner that will minimize the level of grid-based electricity consumption.

[17] The real decline in inverter and battery costs capture effects of medium- to long-term technological progress, economies of scale, and growing demands on inverter and battery costs on economic performance are considered. Based on values used by Liu, O’Rear et al. (2014).

[18] Low-end average cost of module system installation ($2018/Watt) in the state of Maryland (https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/)

[19] This price falls within the range of typical costs for 100 Amp subpanel breakers.

[20] Based on SolarCity photovoltaic module study by Meisel et al. (2016).

[21] Residential energy storage systems are only eligible for the ITC if they are charged using only renewable energy sources. The ITC will not be applicable to the battery bank in this analysis given our assumption that the batteries can be charged via the PV system or the grid.

cash purchase of the PV system with and without battery storage; and (2) partial financing (20 % down payment) at a nominal interest rate of 4.60 % and a 20-year financing period.[22]

Table 2. Economic analysis parameters

Parameter	Units	Value
Annual Energy Consumption	kWh	11 874
Annual PV Production*	kWh	16 629
Electricity Consumption Rate	2018$/kWh	0.143
Net Metering Rate**	2018$/kWh	0.065
Fixed Electricity Fee***	2018$/year	98
Discount Rate (Real interest rate)	%	3
Federal ITC	%	30
Maryland Sales Tax	%	6
Loan – Down Payment	%	20
Loan – Nominal Interest Rate	%	4.60
General Inflation Rate****	%	2.1
Loan – Real Interest Rate	%	3
Financing Period	Years	20
Study Period	Years	25
* No degradation considered ** Net metering rate set equal to PEPCO generation charge *** Based on PEPCO Maryland monthly fixed customer charges **** Current U.S. inflation rate as of February 2018		

We calculate the resilience-related values for cost per unserved electricity (CUE) in $/kWh to the homeowners and others in the home (avoided damages and losses) using the Interruption Cost Estimate (ICE) Calculator (Sullivan, Schellenberg, and Blundell 2015). The ICE Calculator is a “tool designed for electric reliability planners at utilities, government organizations or other entities that are interested in estimating interruption costs” (ibid.), which provides estimates of aggregated direct and indirect costs reported as the CUE. Given the parameters of the model upon which the ICE Calculator is built, we limited our analysis to two two-day (48 hour) outages in a given year; we also recognize that no data was available for the U.S. Northeast/mid-Atlantic regions (Sullivan, Schellenberg, and Blundell 2015). We assume the location is Maryland and use the default settings for the ICE Calculator. Furthermore, we assume a household income of $ 75 847 per year, which was the median income of households in Maryland in 2015 (Maryland Department of Planning 2016). We also use several assumed values of indexed reliability of electricity distribution to estimate the CUE values for this case study. These details are calculated using details of consumer interruptions from the past year (or several years). These indices are defined as follows:

$$\text{System Average Interruption Frequency Index (SAIFI)} = \frac{Total\ number\ of\ sustained\ interruptions\ in\ a\ year}{Total\ number\ of\ consumers} \tag{3}$$

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[22] The nominal interest rate is the projected average mortgage rate for 2018.

System Average Interruption Duration Index (SAIDI) = $\frac{Total\ duraation\ of\ sustained\ interruptions\ per\ year}{Total\ number\ of\ consumers}$ (4)

Consumer Average Interruption Duration Index (CAIDI) = $\frac{SAIDI}{SAIFI}$ (5)

Much of the data used in this valuation are of local indices that arise from reports from Pepco, which is an electricity company that has a large market share in the DC-MD-VA metro area (DC PSC, 2015). Table 3, below, provides the values for SAIFI, SAIDI, and CAIDI calculated from reported index values by Pepco and scaled in minutes from the perspective of the individual homeowner.[23]

Table 3. SAIFI, SAIDI, CAIDI values and resulting CUE values

SAIFI	SAIDI	CAIDI	Cost Per Unserved kWh ($2015)	Cost Per Unserved kWh ($2018)
1	960	960	1.50	1.57
2	480	960	1.65	1.73
1	163.8	163.8	2.34	2.45

These CUE values are then applied to the kWh the homeowners require to not incur direct or indirect costs from an outage—resulting in the costs avoided by having backup generation. As noted previously, the range of potential CUE values is large and depends upon evaluation methods as well as the consumer preferences. For demonstration purposes we take three values for CUE from Shivakumar et al., 2017 – low, high, and average values. These CUE values and their sources are reported in Table 4.

Table 4. CUE values ranges taken from Shivakumar et al., 2017

Cost Per Unserved kWh (€2017)	Cost Per Unserved kWh ($2017)	Cost Per Unserved kWh ($2018)
3.20	3.84	4.02
15.80	18.98	19.85
8.70	10.45	10.93

This study varies the two 48-hour grid outages occur every 5 years, 3 years, 2 years, and annually. Doing so, allows exploration of linkages between the economics of investments in PV with battery storage and the amount of time between major grid outage occurrences. LCC analysis under alternative assumptions for the cost and economic parameters are performed for three different versions of the NIST Net-Zero Energy Residential Test Facility: (1) *NZ-Grid*, (2) *NZ-PV*, and (3) *NZ-PV+Storage*. Design case 1 (*NZ-Grid*) assumes that the NZERTF electricity load is satisfied exclusively by way of grid interconnection and does not utilize rooftop solar PV. Case 2 (*NZ-PV*) uses both rooftop PV and grid-based electricity to meet household energy loads. Any excess electricity generated by the PV system is sold back to the grid at the net metering rate shown in Table 2. The

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[23] Personal communication. Joshua Schellenberg. ICE Calculator. March 7, 2018.

residential load for design case 3 (*NZ-PV+Storage*) is satisfied through the grid, the rooftop PV system, and on-site battery storage. The battery bank can be charged either through the grid or from excess PV generation.

4. Results/Discussion

4.1. Economic Assessment

Under the assumptions of a full cash purchase, the results in Table 5 show that investment in rooftop solar only (*NZ-PV*) is always an economically viable alternative relative to the base case (*NZ-Grid),* becoming increasingly less cost-effective as the frequency of grid outages increases. Conversely, investment in rooftop PV with energy storage (*NZ-PV+Storage*) becomes increasingly more economical as the frequency of outages and/or the value of damages and losses increases. The PV with battery storage option only becomes a viable alternative to the base case for high levels of damages and losses (> $891). At a loss of $2422, PV with storage proves to be a more practical investment alternative than the PV-only installation case for two 48-hour outages occurring annually. The same holds true for a cost of $4398 and outages occurring every three years or less.

Table 5. Net savings relative to NZ-Grid design (cash purchase)

		Damage Costs/Losses Avoided—Resilience Values					
		$348	$382	$542	$891	$2422	$4398
Outage Frequency		**Net Savings**					
5 years	*NZ-PV*	$11 551	$11 551	$11 551	$11 551	$11 551	$11 551
	NZ-PV+Storage	-$8 428	-$8 314	-$7 789	-$6 445	-$1 624	$4 857
3 years	*NZ-PV*	$11 496	$11 496	$11 496	$11 496	$11 496	$11 496
	NZ-PV+Storage	-$7 706	-$7 516	-$6 640	-$4 729	$3 660	$14 486
2 years	*NZ-PV*	$11 424	$11 424	$11 424	$11 424	$11 424	$11 424
	NZ-PV+Storage	-$6 635	-$6 345	-$5 011	-$2 102	$10 671	$27 156
Annual	*NZ-PV*	$11 195	$11 195	$11 195	$11 195	$11 195	$11 195
	NZ-PV+Storage	-$3 655	-$3 049	-$3 655	$5 808	$32 467	$66 875

Despite increasing costs given the use of loan financing to purchase system equipment, similar trends in economic performance across outage occurrences and losses are observed (results not shown). A stark difference between the full cash and loan financing options occurs when damages and losses total $ 2 422. In this instance, PV with battery storage proves to be a more practical alternative overall for outages occurring every 2 years or less.

Figure 1 displays the different payback periods for investment in PV with battery storage given alternative outage frequencies and estimates of damage costs/losses.[24] Based on the use of a simple payback metric, Figure 1(a) suggests that all initial investment costs can be recouped given an assumed study period of 25 years. As the occurrence of outages increases from every 5 years to every year (Annual) the number of years required to recover the initial investment either remains constant or decreases. For example, at a combined damage cost of $4398 the payback period for outages occurring every 5 years, 3 years, 2 years, and annually are 25 years, 13 years, 10 years, and 7 years, respectively. The modified

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[24] Lack of data points for damage costs/loss estimates suggest there is no valid payback period under the assumed analysis conditions.

or discounted payback period results in Figure 1(b) highlight less promising outcomes with investment recovery only occurring in cases where damage costs total $891 or greater. For a given level of damages, the length of time required for full investment recovery declines as the outage frequency increases. Unsurprisingly, the chance of investment recovery becomes increasingly more likely as the occurrences of grid-neutral power outages increases.

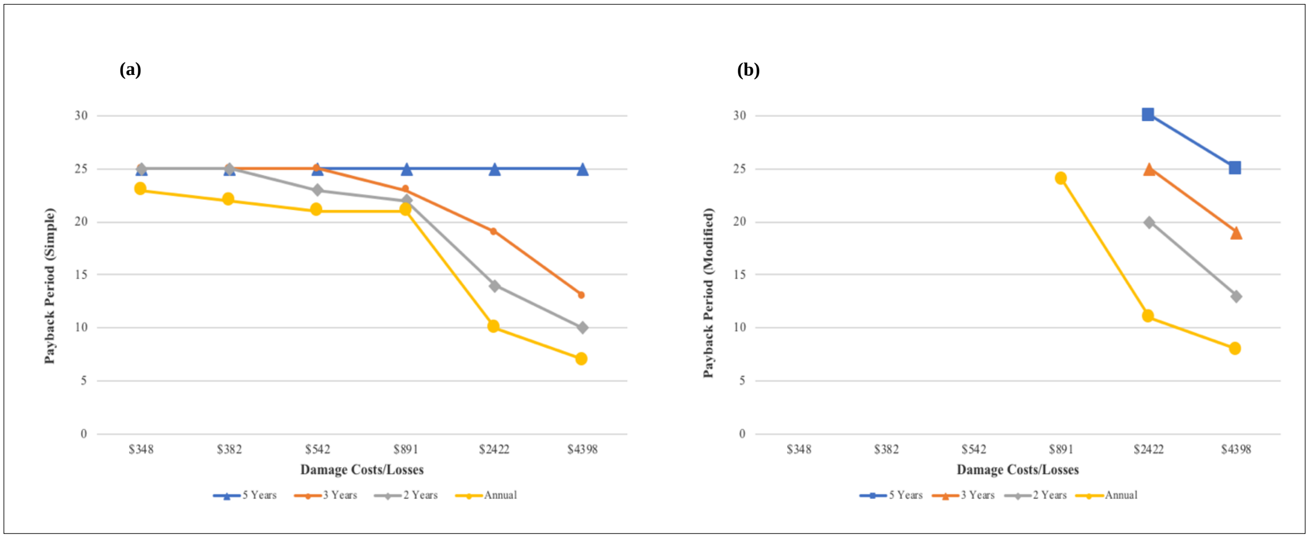

Figure 1. (a) Simple vs. (b) Modified Payback Periods Across All Grid Outage Frequencies for Investment in Resilient Solar

4.2. Environmental Assessment

The LCA environmental results were not the focus of this study – however, they are included to highlight the fact they can be included in the analysis through our framework. With the *NZ-Grid* design serving as the baseline (indexed at 1), the radar plot in Figure 2 reveals that the consequences of including the 10.2 kW solar PV system (*NZ-PV*) are increased levels of Ecological Toxicity, Eutrophication Potential, Criteria Air Pollutants, and Non-Cancer Effects.

Reductions in environmental impacts are observed in only 4 of the 12 environmental impact categories (i.e., Primary Energy Use, Smog Formation, Acidification Potential, and Global Climate Change Potential). The additional impacts of including battery storage (*NZERTF-PV+Battery*) are not included in the figure given our lack of access to LCA data on lithium-ion batteries. However, it is likely that inclusion of battery storage would increase the environmental footprint relative to the *NZ-PV* design.

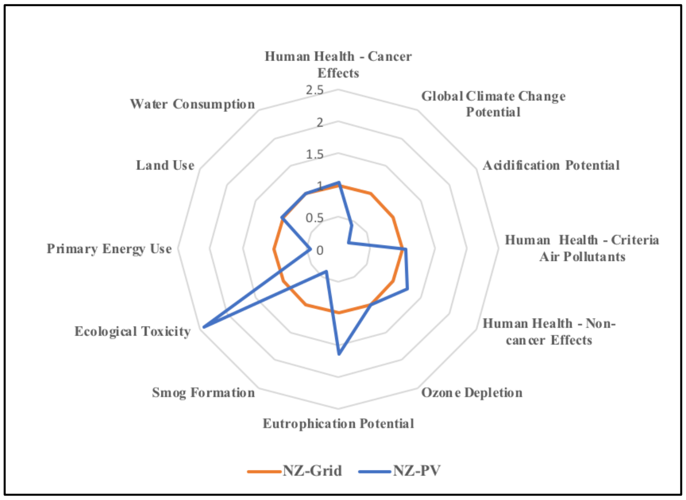

Figure 2. Radar Plots of Alternative NZERTF Designs

5. Conclusions & Further Research

This preliminary study demonstrates that even though a PV and storage system may not appear to be economical under traditional cost-benefit calculations, placing a value on the avoided losses from avoided grid disruptions can make a PV and storage system a more fiscally sound investment. If users are already planning to get PV panels, it is worthwhile to think about a system that leverages that sustainable option (opposed to other resilience options, such as a diesel generator). Though not significant, there are cost savings up front and a quicker payback period when the analysis considers resilience. Furthermore, the valuation of resilience highlights the importance of considering socio-economic valuation of electricity supply interruptions – in particular, resilience, more generally.

In the future, we plan to test this valuation approach that combines sustainability and resilience co-benefits to address other relevant new construction and retrofit options for a residential home, such as the use double-paned glass to make one's home more energy-efficient and/or more resilient to local wildfires. There is value to extending this specific example of solar-plus-battery to consider variations in the following relevant categories: (1) types of end-users; (2) time of occurrence, (3) duration, (4) advanced notification, (5) perceived reliability by the consumer, and (6) outage source.

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