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1 **Economic Feasibility of Campus-Wide Photovoltaic Systems in New England**

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25 **ABSTRACT**

26 Compared to the national average residential retail electricity price, Connecticut (CT) had the 4th
27 highest electricity price in the country with 19.23 cents/kWh in September 2015, nearly 50%
28 higher than the national average for price of electricity. This study aims to assess the economic
29 feasibility of the solar PV systems at the campus under realistic constraints, by analyzing actual
30 data from the solar array on campus. The project focused on the economic feasibility of solar PV
31 systems on campus with physical, spatial, and practical constraints that result in a project to
32 deviate from theoretical (estimated) values. To achieve that, the prediction of the PV power
33 generation from the building was developed and compared with the actual (measured) data.

34 The average payback period of a campus-wide PV system was calculated as primarily 11
35 years, within a range of 8-12 years, and was estimated to reduce overall building operating
36 expenses by \$250,000, or 8%. The economic parameters such as NPV and IRR also validated the
37 investment worthiness. The results of the study could be used to analyze or further develop
38 feasibility studies of PV systems at other universities in Connecticut and neighboring states that
39 share similar climatic characteristics and economic factors.

1 Keywords

2 Renewable energy; Solar photovoltaic; Economic feasibility study; Environmental
3 impact; Campus-wide PV; New England
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9 Highlights

- 10 ○ Feasibility of the campus-wide PV system in UNH was evaluated based on the
11 performance data from Celentano Hall.
- 12 ○ Theoretical estimation of solar energy production was calculated to compare with
13 the actual PV performance data.
- 14 ○ Results could promote interests and investments in renewable energy research and
15 sustainability projects.
- 16 ○ A 67 kW PV system in New England is expected to generate a cumulative cash
17 flow of \$ 360,000 over its 25 years lifetime.
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1 **1. Introduction**

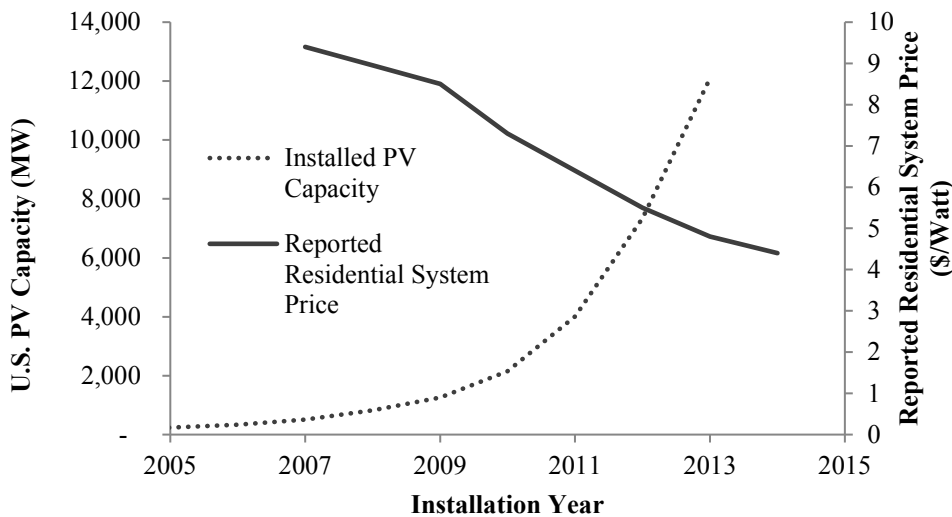
2 In 2014, the U.S. generated about 4,093 billion kWh of electricity, of which
3 approximately 67% were derived from fossil fuels, namely coal, natural gas, and petroleum. The
4 share of renewable energy sources in the electricity grid were minimal, with electricity from
5 wind contributing 4.4%, and solar 0.4% [1]. The problems are exacerbated not only due to
6 consumption of non-renewable fuel sources for electricity generation, but when these facts are
7 evaluated in light of the 2015 United Nations Climate Change Conference, also known as the
8 2015 Paris Agreement to Combat Climate Change, in which participating countries have agreed
9 to work towards keeping global temperature rise below 2°C compared to pre-industrial levels [2].

10 The Paris Agreement acknowledges that meeting this goal will require all countries to
11 take steps to curb their greenhouse gas emissions as soon as possible. Even before signing of the
12 international Agreement, the U.S. had committed to reduce its greenhouse gas emissions by 26-
13 28% from the 2005 levels by the year 2025 [3-4]. Considering that the electricity sector was the
14 largest source of U.S. greenhouse gas emissions in 2013 and was responsible for 31% of the total
15 amount of 6,673 million metric tons of CO₂, it is evident that policies and agreements that aim to
16 curb greenhouse gas emissions would not succeed by disregarding the electricity sector [5].

17 Switching to renewable forms of energy has important economic and social benefits in
18 addition to direct environmental benefits in the form of less pollution derived from energy
19 generation. Creation of new green jobs, developing a more resilient energy infrastructure, and
20 enabling a more competitive energy market would benefit the society overall while opening new
21 markets and sectors for growth [6].

22 A necessity for solar PV technology to gain a foothold and provide a noticeable portion
23 of grid electricity in the U.S. is that cost of electricity from solar PV must be economically
24 competitive with other, more conventional forms of electricity generation [7]. This requirement
25 by itself may not be too difficult as historical trends indicate a rapidly declining cost for solar PV
26 technologies and an exponentially increasing installed capacity, as presented in Figure 1.

27



28 **Figure 1.** U.S. Solar PV installed capacity and reported residential system price [8-10].

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1 Solar PV applications in the U.S. were not distributed uniformly. In 2015, almost 40% of
2 distributed PV capacity was located in California, and the next 9 top states had a share of 44%.
3 The remaining 40 states and the District of Columbia shared the remaining 16% installed
4 capacity. As of September 2015, Connecticut was the 10th state with the largest installed solar
5 PV capacity with 129 MW [11].

6 Through research efforts via the Sunshot Initiative under the U.S. Department of
7 Energy's Office of Energy Efficiency and Renewable Energy, the cost of solar PV has been
8 reduced drastically in recent years. A significant drop in utility-scale cost of electricity from PV
9 projects has been reported in a few years since program initiation, with installed costs dropping
10 from 21.4 cents/kWh in 2010 to 11.2 cents/kWh in 2013, with a further goal to reduce costs to 6
11 cents/kWh by 2020 [12]. Even with the 2013 unit price, solar PV is already cost-competitive
12 with traditional energy sources for electricity generation in certain states and regions. The
13 electricity price in Connecticut is one of the highest in the nation. Compared to the national
14 average residential retail electricity price of 13.06 cents/kWh, Connecticut had the 4th highest
15 electricity price with 19.23 cents/kWh in September 2015, nearly 50% higher than the national
16 average for price of electricity [13].

17 Ma, et.al. [14] investigated the quantified impacts of climate change on the future
18 performance of PV roof system with a general electricity load and legal maximum size of solar
19 array. The morphing method in the study was employed and simulated the long-term
20 implementation of the systems in Australian states. Results show that for the PV system in the
21 majority of cities, a 10–20% increase of economic costs between the 2030 and 2050 climate
22 scenario would be required.

23 A study conducted by Baurzhan, et.al. [15] shows that with an estimated annual rate of
24 decrease in PV system costs of 4% and 7.67 % in Sub-Saharan Africa, solar home systems are
25 expected to become very competitive with conventional diesel electricity generators within 9 to
26 17 years. This study also insists of necessity of government incentives for the initial development
27 in PV market. A similar cost-effective policy study [16] was conducted in India.

28 The Desert Research Institute [17] installed eight solar PV systems in Nevada with total
29 nameplate capacity of 2.4 MW. The PV systems supply approximately 40% of total electricity
30 used at DRI's two campuses. For the six systems larger than 50 kW, the simple payback period
31 of 14.4 to 26.7 years were estimated, and 25 year return on investment showed double for some
32 systems. Another solar PV feasibility study [18] details the multi-level estimation methodology
33 used to estimate rooftop PV potential in the commercial and residential sectors in three states
34 including California, Arizona, and New Jersey. Those three states account for two-thirds of the
35 cumulative installed PV capacity in the U.S. The estimation methodology in the study shows that
36 rooftop PV could provide 35%, 43%, and 61% of state electricity demand in New Jersey,
37 Arizona, and California, respectively. The paper concluded that these states could increase
38 current installed distributed PV capacity by 20, 30, and 40 times, respectively.

39 Perhaps an equally significant barrier to further advancing the system-wide integration of
40 solar PV would be the lack of public awareness of the potential benefits of the technology. The
41 social and economic barriers of actual and perceived cost differential between electricity price of
42 solar and conventional sources of energy, together with a lack of awareness of the potential
43 applications of PV technology into the built environment remains to be solved for solar PV to
44 achieve desired market penetration.

45 University campuses are prime targets to implement solar PV technology for multiple
46 reasons. They act as incubators for new ideas and places where research takes place. They also

1 educate future generations not solely in their respective discipline, but also by the physical
2 environment that they are exposed to. Hence, exposure to solar PV through campuses combined
3 with effective communication on generation rates and the feasibility of the system would
4 contribute towards overcoming the social and economic barriers related to solar PV technologies.
5 A more pragmatic reason for campuses to implement solar PV would be the American College
6 and University Presidents' Climate Commitment (ACUPCC) agreement, where commitments are
7 made to reduce campus-wide greenhouse gas emissions and environmental impacts. There were
8 679 signatory institutions as of 2014, which cumulatively represent 41.6% of U.S. students in
9 higher education [19-20]. As was discussed previously, an effective policy aiming to curb
10 greenhouse gas emissions must take energy generation into account.

11 A 42 kW PV system and a 50 kW wind turbine system were installed to reduce energy
12 use from the electrical grid consumption at West Texas A&M University (WTAMU).
13 Alternative Energy Institute (AEI) [21] at WTAMU performed the installation of the PV and
14 wind turbine systems and conducted feasibility study. The AEI also developed the solar and
15 wind maps that show potential renewable energy places in Texas.

16 The goal of the study was to assess the economic feasibility of expanding solar PV
17 systems at the University of New Haven (UNH) campus under realistic constraints, by analyzing
18 data from a recently implemented solar array on campus. To achieve that, the prediction of the
19 PV power generation from the building was developed and compared with the actual (measured)
20 data. The results of the study could be used to assess the feasibility of PV systems at other
21 universities in the state of Connecticut (CT) that share similar climatic characteristics and
22 economic factors. Solar energy generation was estimated by using actual weather data and by
23 determining favorable roof pitches and cardinal directions of UNH buildings. The payback
24 periods were estimated individually for each building and optimal buildings have been identified.
25 Other universities especially in CT and the New England region could directly benefit from the
26 economic analysis presented here as they would have similar, if not exactly the same, electricity
27 costs as well as offered incentives.

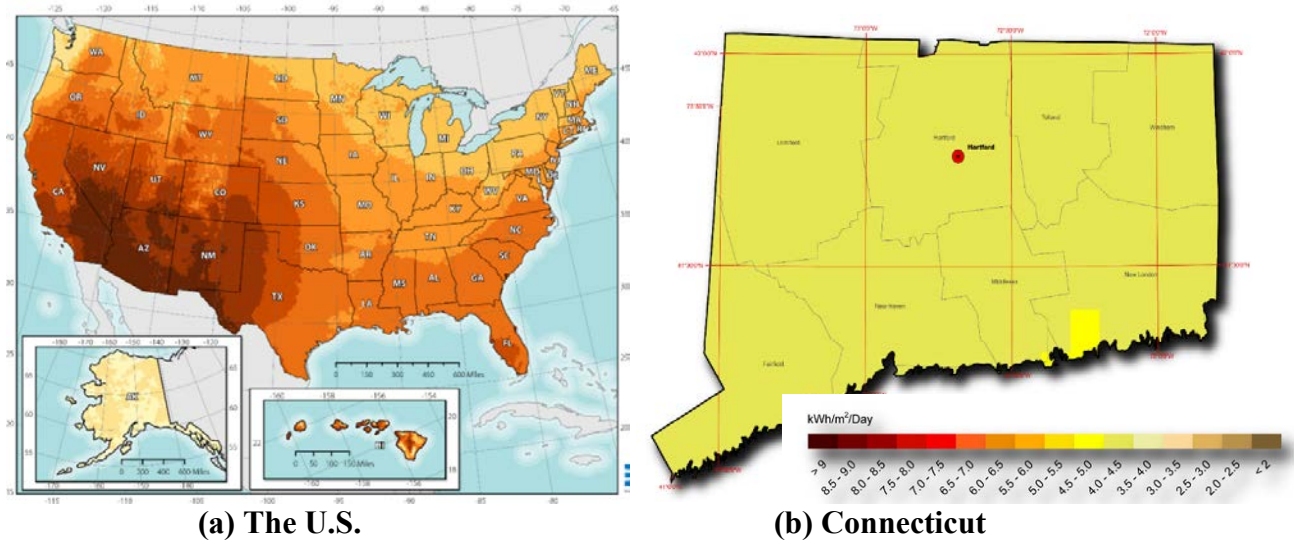
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29 **2. Background**

30 **2.1. University of New Haven (UNH) Campus**

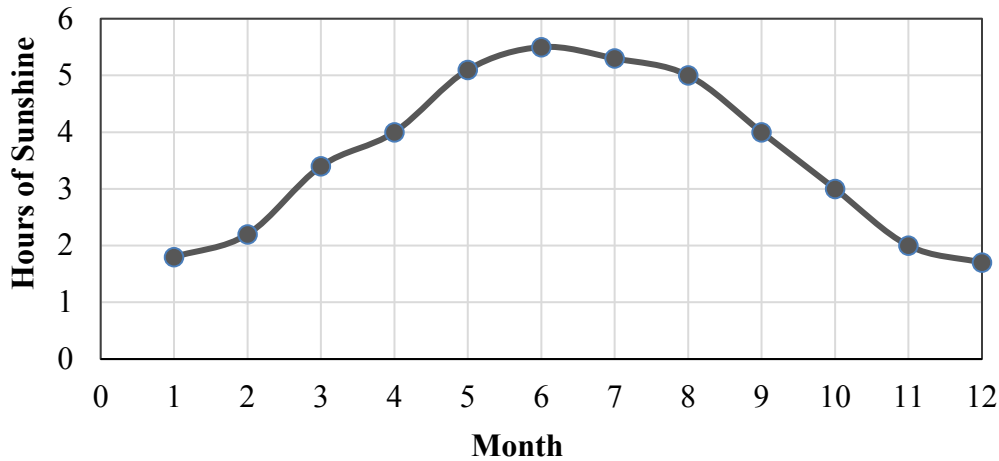
31 UNH is located in West Haven, Connecticut, and thereby lies in the Northeast region of
32 the U.S. A solar insolation map (see Figure 2) developed by NREL in 2012 indicates that the
33 state of CT overall has 4.5-5.0 kWh/m²/day of PV solar resource [22], which places the region in
34 an average rating for solar resource. As for other climatic characteristics, the region has a humid
35 continental climate with hot summer days. The daily temperature typically varies between -4°C
36 and 29°C over the course of a year and seldom drops below -12°C or goes above 31°C.
37 Annually, 206 days equivalent to about 2,600 hours of sunshine are present, with a distribution
38 as shown in Figure 3. Geographically, the campus is located in the northern hemisphere with a
39 latitude of 41.29° and a longitude of -72.96°.

1



2
3 **Figure 2.** Solar resource map of the U.S. and Connecticut

4



5
6 **Figure 3.** Average monthly solar insolation in Connecticut

7

8 UNH is a medium-sized Master’s level institution of higher education with over 6,000
9 undergraduate and graduate students. The main campus is located in a suburban setting, and is
10 surrounded by residential zones. As land on campus is scarce, and opportunities for expansion
11 are hampered by surrounding existing development, the optimal location for a solar PV system
12 would be the roofs of buildings on campus. There are 26 buildings on the UNH campus with a
13 total of 30,000 m² of roof area that was found to be structurally suitable for solar PV
14 implementation.

15

16 **2.2. Celentano Hall PV System**

17 Celentano Hall was the first green building certified by the U.S. Green Building Council
18 at the University of New Haven campus. The building has received LEED gold certification

1 status. Celentano Hall is an upper classman residence hall for undergraduate students living on
2 campus. The building has 402 beds and is occupied primarily by juniors and seniors.

3 A solar PV array was implemented on the roof of the building recently, which provided
4 actual data analyzed in this study. The system consisted of 228 modules of Hanwha HSL 72
5 model on Panelclaw Polar Bear racking and three Solectria inverters [23]. Based on an active
6 islanding detection technique [24], three inverters were used in the system to improve efficiency.
7 The fixed panel array system of 228 PV modules were south facing with an inclination of 12
8 degrees. Considering 5% to 10% of the total energy generated is needed to operate the tracking
9 system, fixed panels were determined to be more economically feasible for the Celentano Hall
10 PV system [25]. Figure 4 was taken during system installation, where the inclination can be
11 observed. The installation of the fixed mount array with a system size of 67.27 kW was finished
12 in December 2014, and the PV system has started generating electricity in January 2015. Table 1
13 further presents the specifications of the installed PV system on Celentano Hall. While PV
14 module design lifetime was taken as 25 years based on the manufacturer's guarantee period,
15 research has shown that lifetime of PV modules may extend well beyond 25 years [26].
16



17
18 **Figure 4.** PV module on the rooftop of Celentano Hall
19

20 While the total roof area of Celentano Hall is 2,186 m², a measurement for the entire roof
21 area cannot be used in array size calculations due to several technical factors. The array size
22 needs to be designed to avoid shading caused by parapets on the sides of the roof in order to
23 maximize unit efficiency, and also to leave gaps between front row modules and those behind it,
24 as the modules are at an incline rather than lie flat on the surface, and thus create the potential to
25 shade modules placed behind them. Furthermore, PV modules are typically set 4-6 feet from the
26 edges of a roof for safety reasons, as well as to provide accessibility during maintenance visits.
27 Also, the roof of an existing building, as was the case with Celentano Hall, already contained
28 obstacles such as AC units and water tanks that required the PV design to conform around those
29 objects. Existing objects on the roof of Celentano Hall together with the final layout of the PV
30 array system fitted based on project constraints is presented in Figure 5.

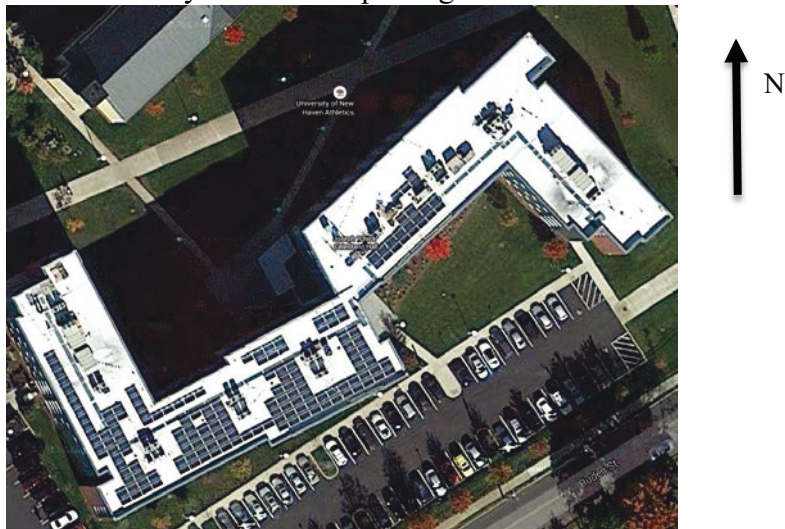
1 **Table 1.** Celentano Hall PV system specifications and design criteria used in the analysis [23-27]

Roof Height	55 feet	Module Brand and Model	Hanwha HSL 72P6-PB-4-300Q
Module Inclination	12 degrees	Module Surface Area	1.93 m ²
Azimuth (West/East Building)	152/134 degrees	Module Efficiency	15.50%
Setback from Roof Edge	4 feet	Racking	Panelclaw Polar Bear III
Roof Parapets	2 feet	Inverter	Solectria PVI20TL
Temperature Range	6-91 °F	Connection	Grid Inter-Tie
Design Wind Speed	110 MPH	System Capacity	67.26 kW
Estimated Annual Module Degradation	0.5%	Module Design Lifetime	25 Years

2
 3 The total panel area can be calculated by multiplying the number of modules installed
 4 and the surface area of each module, thereby yielding 440 m². By comparing the resulting
 5 number with the total roof area of 2,186 m², it is clear that the system size implemented may be
 6 significantly smaller than the roof area of a building.

7
 8 **2.3. Solar PV Installations in Other Institutions of Higher Education in Connecticut**

9 Through the National Center for Education Statistics, the Department of Education lists 28
 10 universities and colleges in the state of Connecticut that offer a Bachelor’s or higher degree.
 11 However, the Association for Advancement of Sustainability in Higher Education (AASHE) list
 12 only 7 higher education institutions that have an installed PV system. Reviewing publicly
 13 available information of the remaining 21 institutions did not yield further information. The PV
 14 system installed by UNH and analyzed in this study was not yet reported by AASHE but has
 15 been added to Table 2, which presents the 8 higher education institutions in CT that have an
 16 installed PV system on campus together with their installed capacity.



17
 18 **Figure 5.** Aerial view of Celentano Hall PV array

19
 20

1 **Table 2.** List of higher education institutions in Connecticut with PV systems [28-32]

Institution Name	Year Completed	Capacity (kW)
Connecticut College	1998	43
	1999	10
Fairfield University	2001	15
Quinnipiac University	2010	224
Southern Connecticut State University	2011	50
University of Hartford	2006	17
University of New Haven	2014	67
Wesleyan University	2008	7
	2012	200
Yale University	2007	40
	2009	25
	2010	100
	2015	1,250

2
3 It is also important to keep the environmental benefits of such PV installations in
4 perspective. As an alternative to traditional fuel sources, electricity generation from PV systems
5 avoids CO₂ emissions associated with electricity generation. While there have been different
6 attempts to account for avoided CO₂, a recent prominent method that was developed by EPA is
7 the Avoided Emissions and Generation Tool (AVERT). The primary intent of the tool was to
8 enable states and other interested stakeholders to assess air pollution reduction measures [33].
9 Accordingly, utility scale PV systems in the Northeast region of the U.S. would avoid 0.53 tons
10 of CO₂ per MWh [34]. The value was verified by comparing to results of recent studies. A news
11 article regarding Yale University’s most recent plans to install a 1,250 kW PV array reports
12 estimated electricity generation of 1.6 million kWh annually, where the system would reduce
13 16,000 metric tons of CO₂ emissions over its life time [35]. Assuming a 20 year design lifetime,
14 the coefficient for avoided tons of CO₂ per MWh can be calculated to be in accordance with the
15 results from the AVERT tool.

16 Another study conducted by University of Connecticut for their main campus in Storrs,
17 estimated similar results for avoided CO₂ emissions. It was reported that a PV system with a 10
18 kW size would be expected to generate 11,520 kWh per year, and reduce 10,575 lbs. of CO₂
19 emission annually [36]. However, this study was also important as their research aimed to
20 calculate economic viability of renewable energy technologies by including initial cost and total
21 cash flow, but also addressed other benefits such as avoided greenhouse gas emissions, and
22 enhanced education and research opportunities. Nevertheless, the report concludes that for PV
23 systems to be a viable alternative, there needs to be strong government support in the form of
24 grants, tax credits, or accelerated depreciation benefits [36]. A major shortcoming of the report is
25 its lack of a transparent economic model that other universities in the region could benefit from.
26 It is intended that the current study would fill an information gap in this field and aid other
27 universities interested in installing PV systems on campus.

2.4. Regional Economic Impacts of PV Systems

The Jobs and Economic Development Impact (JEDI) Model developed by NREL can be used to estimate the economic impact of renewable energy installations for a specific region. Economic impacts related to on-site labor impacts, local revenue and supply chain impacts, as well as induced impacts are captured within the tool [37]. There have been studies that assessed the jobs impact of solar PV applied at the state level in the U.S., or in other countries [38-43]. Rather than apply the tool at the state level however, an analysis was conducted as part of the study for the PV system installed at Celentano Hall, as well as an additional analysis to assess the economic impacts of expanding solar PV installations to the entire campus.

2.5. Procurement Strategies

There are two different procurement strategies for installing PV systems on university campuses. Each strategy can benefit from different types of financial incentives. The first strategy is to have a third-party private company own the solar array and lease them to the university. In this case, the university would need to make a power purchase agreement (PPA) with the company, usually at a higher electricity rate than what would have been paid to the supplier utility. The third-party company takes advantage of tax credits and deductions offered at the federal and state levels. The university would be relieved of high initial installation costs associated with PV array systems.

The second strategy would be for the university to be the sole owner of the PV system. While this strategy prevents campuses from paying higher electricity rates to a third-party company through a power purchase agreement, as most colleges and universities in the U.S. are non-profit institutions, they cannot take advantage of the 30% tax credit on installation costs, hence affecting the feasibility of the system and reflecting on electricity rates generated throughout the life of the system.

Regardless, UNH opted for the second option of owning the PV system as it was deemed a better alternative as a long-term investment compared to buying back electricity at a higher rate through a PPA. However, UNH was able to benefit from the Zero Emission Renewable Energy Credits (ZRECs) incentive offered by the state.

2.5.1. Zero Emission Renewable Energy Credits (ZRECs)

In July 2011, the state of Connecticut enacted legislation amending the state's renewable portfolio standards and created new classes of renewable energy credits for PV systems with a project size larger than 100 kW and up to 1 MW in nameplate capacity [44]. The amount of ZRECs award depends on the amount of electricity generated; therefore, the amount decreases every year because of the degradation factor (0.50 %) of PV modules. ZRECs were awarded to the installed Celentano Hall PV system. A PV system with capacity greater than 100 kW qualify for reverse auctions, and systems with capacity less than 100 kW would earn benefits through a lottery system. Being below the 100 kW cutoff level, UNH could still receive substantial financial support for 15 years as long as the system continues to operate as designed. Celentano Hall was awarded \$0.148/kWh electricity generation by the PV system.

3. Methods

The goal of the study was to assess the economic feasibility of expanding solar PV systems on the UNH campus by analyzing data from a recently implemented array on campus, and to develop an economic model for use by other universities in Connecticut (CT) which share

1 similar climate characteristics and economic factors. Even though actual data were collected
 2 during the study, estimation of electricity generation was deemed necessary to forecast future
 3 performance of the array, which would then be used in the economic model. The annual energy
 4 production was estimated by using the PVWATTS Calculator together with local and system
 5 variables that were input into the calculator. The payback periods were estimated individually for
 6 each building and optimal buildings have been identified.

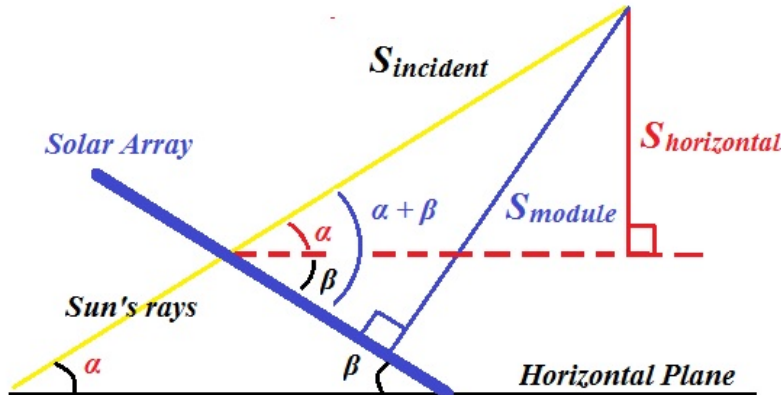
8 3.1. Estimated Electricity Generation

9 In order to conduct an economic analysis, an estimated energy production of the PV
 10 system was deemed necessary. Quantitative equations were used to calculate estimated power
 11 produced by the PV array. Eq. (1) was used to estimate solar energy generation for a flat-plate
 12 collector, facing south at a fixed tilt.

$$13 \quad E = A \cdot r \cdot h \cdot pr \quad (1)$$

14 Where; E is the annual estimated electricity production in kWh, A is the total solar panel area in
 15 m², r is solar panel efficiency, h is annual average solar radiation in kWh/m², and pr is the system
 16 performance ratio.

17 The power incident on a solar panel depends on the solar radiation and the angle between
 18 the module and the sun as shown in Figure 6. The power density on the module surface is at
 19 maximum when the tilt angle makes the module perpendicular to sunlight. However, the
 20 declination angle, α , is changing during the day and therefore, the power density of a fixed PV
 21 module is less than solar insolation.



22 **Figure 6.** Solar radiation on a tilted surface

23
 24
 25 Average solar radiation data from two different data collecting centers was used in the
 26 calculation for more accurate estimation. UNH campus is located at 41.29° latitude between
 27 Bridgeport and Hartford, where weather data collection centers exist. Accordingly, average
 28 horizontal solar radiation at these two sites was both equal to 3.8 kWh/m²/day, and hence the
 29 same value was used to estimate electricity generation at the UNH campus [45].

30 Trigonometric analysis was performed to estimate annual average solar radiation. In
 31 order to calculate the S_{module} shown in Figure 6, α , which is the angle between sunlight and the
 32 horizontal plane can be calculated using equations (2) and (3).

$$33 \quad \alpha = 90 - \phi + \delta \quad (2)$$

$$34 \quad \delta = 23.45 \cdot \sin \left(\left(\frac{360}{365} \right) \cdot (284 + d) \right) \quad (3)$$

1 where; α is the elevation angle, φ is the latitude, and δ is the declination angle. Equation (3)
 2 calculates declination angle of a specific day of a year, and the value ranges in between -23.45
 3 on the first day of the year to + 23.45 on the last day of the year. The elevation angle for the
 4 Celentano hall PV system is calculated to be 48.71 degree. The total annual average solar
 5 radiation can be calculated using Equation (4),

$$6 \quad S_{\text{module}} = S_{\text{horizontal}} \cdot \sin(\alpha + \beta) / \sin \alpha \quad (4)$$

7 where; β is the tilt angle of the module measured from the horizontal.

8 Performance ratio is a measure of the overall efficiency of a PV system, and covers
 9 efficiency losses related to interconnected parts and conversion inefficiencies, and is independent
 10 of location, or the amount of sunlight received. It represents a ratio of actual energy generation to
 11 energy that can theoretically be generated. Values input into the PVWATTS calculator were
 12 presented in Table 3. An overall derate factor of 0.75 was found for the Celentano PV system,
 13 and was used in the study for estimating electricity generation by the installed system.

14
 15 **Table 3.** Derate factors for AC power rating at STC

Component	Performance Ratio	PVWATTS Default	Range
Module Nameplate DC Rating		0.95	0.80 - 1.05
Inverter and Transformer		0.92	0.88 - 0.98
Mismatch		0.98	0.97 - 0.995
Diodes and Connections		0.98	0.99 - 0.997
DC Wiring		0.98	0.97 - 0.99
AC Wiring		0.98	0.98 - 0.993
Soiling		0.95	0.30 - 0.995
System Availability		0.98	0.00 - 0.995
Shading		1	0.00 - 1.00
Age		1	0.70 - 1.00
Overall DC-to-AC Derate Factor		0.75	

16
 17 The solar radiation incident is relatively constant above the atmosphere, while the
 18 radiation at the Earth's surface varies by atmospheric effects, latitude of the location, and the
 19 time of day relative to year. In addition, to enhance the accuracy of solar irradiation forecasting,
 20 the clearness index was also considered. Clearness index (K_T) is the fraction of the solar
 21 radiation transmitted through the atmosphere to reach a horizontal plane at a particular location
 22 of the Earth as shown in Equation (5). K_T indicates how much of the Sun's radiation is
 23 attenuated due to scattering and absorption in the atmosphere, and thus is important measure for
 24 the PV analysis. Table 4 shows the monthly and annual clearness index in two locations
 25 (Bridgeport and Harford) near the project location.

$$26 \quad \overline{K_T} = \frac{\overline{H}}{\overline{H_{oh}}} \quad (5)$$

27 where; \overline{H} is the monthly average daily irradiation on a horizontal plane at the Earth's surface and
 28 $\overline{H_{oh}}$ is the monthly average daily value of extraterrestrial radiation energy falling on a horizontal
 29 plane.

1 **Table 4.** Monthly and Annual Clearness Index (K_T) in Connecticut

CITY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YR
BRIDGEPORT	0.45	0.48	0.48	0.48	0.49	0.5	0.51	0.51	0.5	0.48	0.43	0.42	0.49
HARTFORD	0.47	0.49	0.48	0.48	0.49	0.51	0.52	0.51	0.49	0.47	0.42	0.42	0.49

2

3 **3.2. Economic Analysis**

4 Table 5 shows the financial factors used for the economic analysis calculation. Factors
 5 discussed in academic literature [20], as well as other deemed necessary were included in the
 6 analysis. The annual electricity usage by Celentano Hall was 1,425,900 kWh, and the current
 7 electricity rate for the building was \$0.17/kWh. An annual electric cost increase of 3.5% was
 8 calculated from the average of residential electricity price increases in the U.S. between 2004
 9 and 2014, and was factored into the calculations during the study [40]. The estimated insurance
 10 on the PV system was 0.17% of the total installation cost, which is expected to increase by the
 11 annual inflation rate of 3.0% [47]. The annual operation and maintenance costs were estimated to
 12 be \$10/kW-year [48].

13

14 **Table 5.** Financial factors for the Celentano Hall PV system

No. of Solar Panels	228	Panels	Installation Costs	\$288,500	Turn Key
PV Array Size	67.27	DC kW	Maintenance	\$10.00	/ kW / yr
Annual Solar Production	82,800	kWh / yr	ZREC Reward	\$0.15	/ kWh
Electricity Usage	1,425,900	kWh / yr	ZREC Escalator	0.50%	/ yr
Module Efficiency	15.5	%	ZREC Term	15	yrs
Module Degradation	-0.5	% / yr	Interest Rate	5%	
Electric Cost Escalation	3.5	% / yr	Inflation Rate	3%	/ yr
Current Electricity Rate	0.17	\$/ kWh	Insurance	0.17%	
			Marginal Tax Rate	38%	
			Tax Credits	30%	

15

16 **4. Results and Discussions**

17

18 **4.1. Celentano Hall PV System Performance**

19 Actual electricity generation data from the installed Celentano Hall PV system was
 20 monitored during the project. Consecutive ten-month performance data was collected and
 21 analyzed as part of this research. Table 6 presents monthly electricity generation from the start of
 22 the array's operation together with monthly average temperatures. The peak electricity
 23 generation occurred during summer while low electricity was generated during winter.

24

25 **4.2. Estimation of Annual Energy Production**

26 In addition to collecting actual data as part of the study, estimation of electricity
 27 generation was deemed necessary to forecast future performance of the array, which was then
 28 used as an input into the economic model.

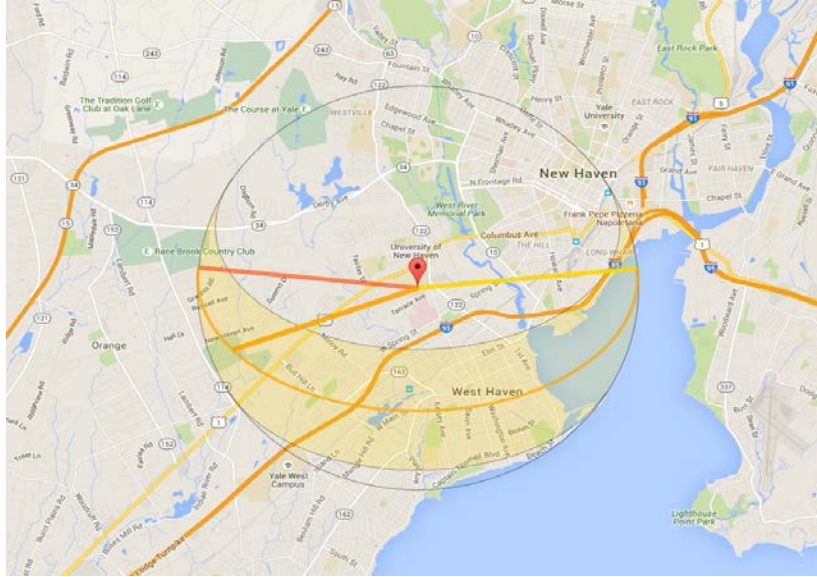
29

1 **Table 6.** Celentano Hall PV system electricity generation (actual) and monthly average
 2 temperatures at the location [49,50]

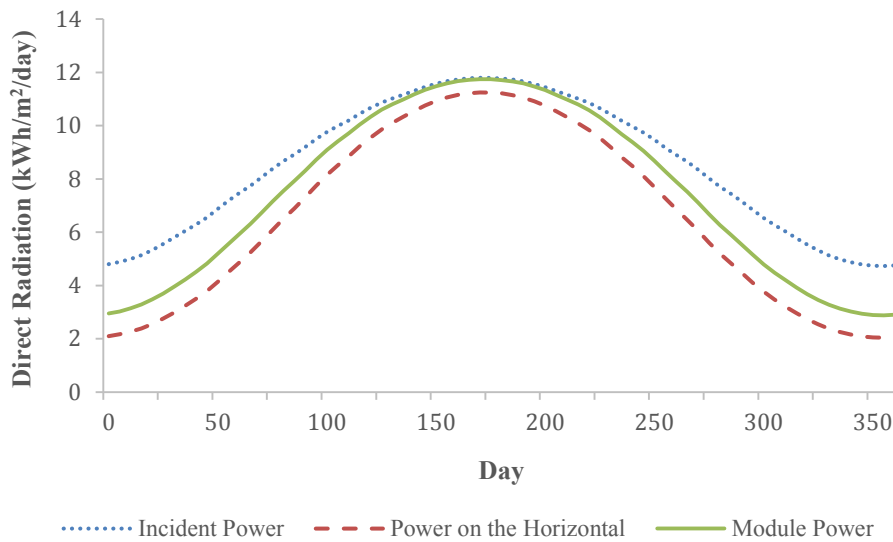
Month	Monthly Electricity Generated (kWh)	Monthly Average Temperature (°C)
January	4,513	0.0
February	2,911	-0.6
March	6,552	3.9
April	7,686	9.4
May	10,735	13.9
June	9,326	18.9
July	10,617	22.2
August	10,547	23.3
September	8,609	18.9
October	6,856	13.3
November	4,115	8.3
December	2,777	2.8
Total	85,244	

3
 4 The annual sun path is one of the most effective environmental factors included in solar
 5 PV performance measurement. The tilt angle of modules has a great impact on the amount of
 6 solar radiation incident collected on the surface. Theoretically, the maximum annual module
 7 power occurs when the modules are facing the sun path as shown in Figure 7(a). Figure 7 (b)
 8 shows the maximum amount of solar insolation with respect to the sun path of the studied region
 9 and the module angle. The most ideal orientation and angle for the Celentano Hall is facing
 10 directly south, at an angle of approximately 12 degrees, and this orientation would optimize the
 11 PV generation at this location.

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(a) Sun path on the studied region (West Haven, Connecticut)



(b) Solar radiation on a tilted module

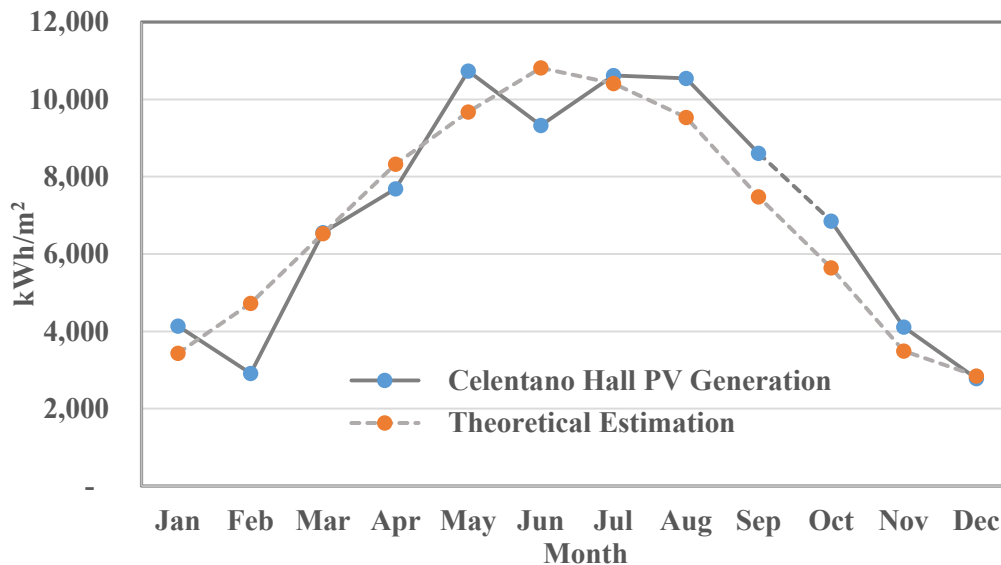
Figure 7. Sun path on the studied region and solar radiation on a tilted module

As shown in Table 7, approximately 82,800 kWh of electricity generation was estimated from the installed Celentano Hall PV system. A comparison between actual and estimated monthly electricity generation of the PV system was presented in Figure 8. While not a perfect fit, the two trends indicate that estimation calculations presented herein may be used to represent the performance of the system in the long run, or at other locations that share similar geographic and climatic conditions.

1 **Table 7. Celentano Hall PV system energy generation calculation**

Celentano Hall PV Array	Latitude 41.29 °	Longitude 72.96 °
Elevation Angle of Sun (α)	48.71	degree
Angle of Module	12.00	degree
Declination Angle (δ)	0.00	degree
Array Tilt (β)	12.00	degree
Latitude (Φ)	41.29	degree
No. of Panels	228	
Panel Size	1.93	m ²
S _{horizontal}	1,393.23	kWh/m ² .y
S _{incident}	1,854.22	kWh/m ² .y
S _{module}	1,617.17	kWh/m ² .y
Annual Solar Energy Output E=A*r*H*PR		
A (Total Solar Panel Area)	440.62	m ²
r (Solar Panel Yield)	0.155	
h (Annual Avg. Solar Radiation)	1,617.17	kWh/m ² .y
pr (Performance Ratio)	0.75	
E (Annual Solar Energy Output)	82,834.10	kWh

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Figure 8. Comparison of actual Celentano Hall PV output and estimated electricity generation

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The actual (measured) data in Figure 8 were collected from January 16, 2015 to April 15, 2016. In the figure, the data for January, February, March, and April were averaged. As actual data are dependent on weather conditions, irregular weather conditions may cause other discrepancies in the trends. For example, more snow or precipitation and cloud cover in February and June were responsible for the mismatch between actual and estimated trends. According to weather history in New Haven, Connecticut, there were more rain or snow days in February and

1 June, 2015 than the normal years. The values on the weather variables could be analyzed by
 2 using the simulation software developed by the FAE group from UFPE (Alternative Energy
 3 Source – Universidad Federal de Pernambuco) [51]. Over the long term however, total electricity
 4 generation of the PV system was expected to be close to the estimated value.

6 4.3. Economic Analysis

7 The turn key installation cost of the PV array was \$288,500 for a PV system with 67 kW
 8 capacity. Annual electricity generation of the system was estimated to be 82,800 kWh/yr. Based
 9 on the financial factors and values assigned during the economic analysis, the installed cost of
 10 the solar PV system analyzed can be calculated as \$4.29/W.

11 It is interesting to note that the calculated value of \$4.29/W is 27% lower than the unit
 12 cost value of \$5.91/W presented as the CT state average by the Open PV Project database,
 13 administered by NREL [52]. Still, the 127.2 MW installed solar PV capacity reported by the
 14 database is reasonably close to the 129 MW proposed by the EIA [13], hence lending credence to
 15 the database. While the difference in unit cost may be due to a number of reasons such as
 16 differences in project size, use of panels that have different technology, or different company
 17 practices, it is important to realize the variation in unit price of installed cost, as the value would
 18 have an important impact on the feasibility and payback period calculations of a project.

19 ZRECs constitute an important determinant in assessing the feasibility of PV systems as
 20 it provides long term support to bring down the unit cost of electricity generated through the PV
 21 system. The installed array was awarded \$0.148/kWh ZRECs for electricity generated by the PV
 22 system. Based on annual electricity generation, the University would receive around \$12,000
 23 during its first year, with a subsequent 0.5% annual decrease due to the module degradation.
 24 Still, UNH would benefit from \$180,000 in financial support provided by the program over the
 25 duration of the incentive.

26 The return on investment (ROI) represents the cost effectiveness of a PV system project.
 27 The profitability and economic aspects of the Celentano Hall PV system were determined by
 28 evaluating the economic indicators: Net Present Value (NPV), Internal Rate of Return (IRR),
 29 Simple Payback Period (SPBP), Discounted Payback Period (DPBP), Discounted Cash Flow
 30 (DCF), and Profitability Index (PI). The life expectancy of the solar panels were assumed to be
 31 25 years as determined by the most of solar companies. The current 30 year fixed loan rate is
 32 3.72 %, and therefore, the discount rate of 5% was used for this analysis [53-56].

33 Net present value is a simple calculation of difference between the present value of cash
 34 inflows and outflows. NPV compares the value of an investment today to the future value of the
 35 money based on inflation and returns. It is one of the most effective value to assess the
 36 profitability of a long term project. A positive value of NPV indicates a favorable investment.

$$37 \quad NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 \quad (6)$$

38 Internal rate of return (IRR) is an economic indicator that analyzes the profitability of a project
 39 by comparing to the discount rate. A project is more desirable as the difference between IRR and
 40 discount rate becomes larger.

$$41 \quad 0 = \sum_{y=1}^y \frac{C_y}{(1+IRR)^y} - C_0 \quad (7)$$

42 The simple payback period evaluates the risk associated with a long-term project. SPBP is the
 43 time required for an initial investment to generate a positive cash flow.

$$44 \quad SPBP = \frac{\text{Initial Investment}}{\text{Annual Savings/y}} \quad (8)$$

Discounted Cash Flow (DCF) is an anticipated revenue stream generated from an investment at a given period. Profitability index (PI) a simple value between 1 and 2 indicating the ratio of payoff to the initial investment. If the PI value of a project is 2, the investment is expected to be doubled within the project life time. Thus, a project with PI value greater than 1 is acceptable. DCF and PI can be calculated using the formulas,

$$DCF = \frac{CF}{(1+r)^y} \quad (9)$$

$$PI = \frac{NPV}{Initial\ Investment} + 1 \quad (10)$$

Table 8 summarizes Cenlentano Hall PV system economic parameters. As shown in the table, the result of the economic analysis on the campus-wide PV system at UNH suggests that the project is profitable since PI is larger than 1.0. The NPV for Celentano Hall PV system is \$81,996, and IRR of 8.74% is well over the discounted rate of 6%, both indicating that the project is profitable. The project is expected to generate a positive cash flow after simple payback period of 11 years.

Table 8. Estimated Cenlentano Hall PV system economic parameters

Net Present Value	(NPV)	\$ 81,996
Internal Rate of Return	(IRR)	8.74%
Simple Payback Period	(SPBP)	11 years
Simple Cash Flow	(SCFy)	\$ 360,290
Discounted Cash Flow	(DCFy)	\$ 106,395
Profitable Index	(PI)	1.28

4.4. Payback Period and Lifetime Savings

The estimated annual solar energy generated by the Celentano Hall PV system during its first year was calculated to be 82,800 kWh. However, electricity generated is expected to decline over the lifetime of the PV system by the factor of module degradation. Based on the analysis presented in Table 9, the installed PV system was expected to generate a positive cash flow in 11 years, hence the payback period. Furthermore, the system was estimated to accrue around \$360,000 by its end of life after 25 years.

4.5. Extension of Economic Analysis to Other Buildings at UNH

Economic analysis for a campus-wide PV system installation was conducted to assess system feasibility for other buildings at the UNH campus. The analysis was based on data obtained for the Celentano Hall PV system, and was extrapolated to other buildings by taking into account their actual characteristics and limitations such as dimensions, roof types, their ability to structurally accommodate additional loads, and historical electricity consumption of each building. After an initial analysis of roof type, size, and orientation, 26 out of 35 buildings were selected for further analysis. The selected 26 buildings, shown in Figure 9, were unobstructed by nearby trees or were not shaded by other nearby buildings, and their roofs were suitable to install PV arrays large enough to qualify for government incentives. The estimated

1 annual energy production and payback periods were calculated based on the same method
 2 described in section 4.4.

3
 4 **Table 9.** Payback period and estimated annual cash flow calculations for the Celentano Hall PV
 5 system up to its 25 year lifetime. Values within parenthesis indicate negative values.

Year	Installation Cost and O&M (\$)	Electricity cost (\$/kWh)	Electricity Generation (kWh)	Electricity Cost Savings (\$)	ZREC Credit (\$)	Insurance (\$)	Effective Cash Flow (\$)	Cumulative Cash Flow (\$)
1	(288,500)	0.170	82,834	14,082	12,259	(490)	(262,649)	(262,649)
2	(673)	0.176	82,420	14,502	12,198	(505)	25,522	(237,127)
10	(852)	0.232	79,180	18,345	11,719	(640)	28,572	(19,781)
11	(878)	0.240	78,784	18,893	11,660	(659)	29,016	9,235
19	(1,112)	0.316	75,687	23,900	-	(835)	21,953	214,123
20	(1,145)	0.327	75,309	24,613	-	(860)	22,608	236,730
25	(1,327)	0.388	73,445	28,509	-	(997)	26,184	360,289

6



7
 8 **Figure 9.** Section of the UNH Main campus aerial view
 9 Note. Shaded areas correspond to building rooftops, where numbers indicate individual buildings. 22 of the 26
 10 selected buildings for further analysis were shown in the figure.

11

12 Each roof was tested for its structural capacity to hold additional weight imposed by solar
 13 panels weighing about 27 kg each. If a roof has to be replaced before the design lifetime of the
 14 PV systems, taken as 25 years in this study, the roof was considered to be unsuitable for new PV
 15 installation as the costs associated with uninstalling PV arrays would be inhibiting [58].

16 A primary concern was the number of potential PV panels that could be practically fitted
 17 onto the roofs of various buildings, as earlier analysis on Celentano Hall had indicated that the
 18 difference between actual and theoretical number of panels could be significant. While roof area

are of Celentano Hall was 2,186 m², only 228 modules corresponding to 440 m² were installed. In other words, each PV module may be assumed to practically require 9.6 m² for installation.

Table 10 present results of the economic analysis extrapolated to the UNH campus through the 26 buildings selected. Assuming similar spatial limitations in the placement of PV modules, a campus-wide PV installation would require somewhat more than 3,500 PV modules. Based on cash flow analysis at system end of life, all PV arrays returned a profit. The payback period ranged between 8-12 years depending on the building and its characteristics.

The average annual electricity savings from a campus-wide PV installation on the roofs of the 26 buildings was estimated to be a \$250,000. Therefore, total savings of approximately \$6.3 million could be expected over the 25 year design lifetime of the system. These numbers should be evaluated with regards to current expenditures of the University. Energy costs make up a significant portion of the overall university operation expenses, where UNH was spending approximately \$3 million annually for electricity.

Table 10. Building characteristics and electricity consumption, estimated electricity generation, and payback period calculated for each building

Bldg. No.	Building	Annual Elec. Consumption (kWh)	Roof Area (m ²)	Estimated No. of Solar Modules	Estimated Annual Generation (kWh)	Cash Flow after 25 Years (\$)	Payback Period (Yr)
1	Arbeiter Maenner Chor	37,789	248	26	9,446	63,650	9
2	Bartels Hall	985,520	1,493	156	56,675	223,711	12
3	Beckerman Rec. Center	719,120	3,755	392	142,417	724,393	11
4	Bergami Hall	597,600	1,196	125	45,413	198,914	11
5	Bethel Hall	980,580	929	97	35,241	128,169	12
6	Bixler Hall	285,480	1,048	109	39,601	171,862	11
7	Bookstore/Security	157,160	702	73	26,521	141,020	10
8	Botwinik Hall	331,840	744	78	54,133	235,248	11
9	Buckman Hall	600,236	1,570	164	59,582	270,522	11
10	Celentano Hall	1,425,900	2,186	228	82,834	360,290	11
11	Charger Gymnasium	531,120	1,651	172	62,489	274,897	11
12	Charger Plaza	270,105	795	83	30,155	201,826	9
13	Dental Center	61,280	805	84	30,518	206,605	9
14	Dodds Hall	948,960	2,133	223	81,018	351,481	11
15	Dunham, Sheffield, Winchester Halls	827,200	3,601	376	136,604	542,258	12
16	Echlin Hall	524,160	897	94	34,151	138,231	12
17	Forest Hills Apartments	207,648	2,916	304	110,445	674,862	10
18	Gate House	37,320	194	30	10,899	66,280	10
19	Henry C. Lee Institute	301,920	389	41	14,896	59,880	12
20	Kaplan Hall	229,506	668	70	25,432	123,095	11
21	Maxcy Hall	700,320	900	94	34,151	143,469	11
22	Peterson Library	117,200	1,380	144	52,316	279,161	10
23	Ruden Street Apartments	66,583	606	63	22,888	154,564	9
24	South Campus Hall	108,760	279	29	10,536	64,765	10
25	Subway Building	15,980	275	29	10,536	92,390	8
26	West Side Hall	117,200	2,340	244	88,647	408,136	11
	Total	11,186,487	33,700	3,526	1,307,543	6,299,679	11

1 Economic benefits of a campus-wide solar PV implementation would have regional
2 impacts as well. Through the use of the JEDI Model, the number of jobs that may be created as a
3 result of the investment was calculated. By inputting project characteristics of the installed
4 Celentano Hall PV system into the model, results indicate that 2 jobs were created locally. While
5 this number is not much, it must be kept in perspective that the installed array was only a 67 kW
6 system. Should the University install PV arrays on the other analyzed buildings, the model
7 yields 31 jobs created during construction and installation and 0.4 jobs during operation years.
8

9 **4.6. Assumptions and Further Discussion**

10 In order to analyze the economic feasibility of Celentano Hall PV system, it is essential to consider
11 the assumptions made on the economic parameters. First, the time period for the financial analysis
12 was considered to be 25 years, which was same as the life expectancies of typical solar panels. The
13 discount rate and inflation rate were also assumed to be constant for 25 years. For the feasibility
14 assessment on the PV system for the entire campus, only ZREC incentive was considered in the
15 calculation because the Celentano Hall only qualified for ZREC. There are more government
16 incentive programs in Connecticut, and a greater profitability can be expected if the project qualifies
17 for other incentives. However, this study was conducted based on the data collected from Celentano
18 Hall, thus the assumption was validated. In order to calculate the expected savings from electricity
19 usage, future electricity rates were assumed to increase by inflation rate of 3% per year, which was
20 determined based on the past electricity rate trend. The operation and maintenance cost for Celentano
21 Hall was estimated to be \$10 per kWh generation. Since the modules for the campus-wide PV system
22 will be managed by the same company, it is acceptable to apply the same rate of O&M to the
23 campus-wide PV economic analysis. Currently only six states mandate 'Feed in Tariff' in U.S. and
24 Connecticut is not one of them.

25 Different methods can be used to achieve the objective of the study, to analyze the
26 feasibility of campus-wide PV system. Solar irradiation at the studied region is required to
27 calculate the theoretical estimation of solar PV generation. While different approaches are
28 available, two most effective methods are clearness index and tilt angle of the module. Since the
29 optimum tilt angle for the studied region was given from the installed PV system, tilt angle
30 method was used to obtain the solar irradiation instead of clearness index, which required
31 complex calculations.

32 The advantages of using NPV as an economic parameter when analyzing a long-term
33 project are its realistic reinvestment assumptions and the ability to modify discount rate, allowing
34 analysis on different risk levels. However, NPV requires assumed value for cost of capital.
35 Depending on the level of assumed cost of capital, the investment can be predicted to be either
36 too low or too high. The advantages of IRR method are it considers the time value of money
37 when evaluating a profitability of a project, and it is simple to interpret. However, the
38 reinvestment assumed for this calculation is unrealistic, because IRR method ignores the actual
39 dollar value of benefits. Discounted payback period shows a reliable result than a simple
40 payback period because it considers the time value of money. However, this method ignores the
41 cash flows after the payback period. Despite the advantages associated with these economic
42 indicators, this study considered the all into analysis, because the results for all indicators
43 validated the profitability of the project.
44

1 **5. Conclusions**

2 The primary objective of this study was to assess the economic feasibility of expanding
3 solar PV systems at the UNH campus under realistic constraints, by analyzing data from a
4 recently implemented solar array on campus. In order to accomplish this objective, an economic
5 analysis model was created based on data collected from Celentano Hall. The annual estimated
6 amount of solar generation was 82,800 kWh, while the total cash flow was calculated as
7 \$360,000 over the design lifetime of the PV system. The payback period calculated by a multi
8 factorial analysis was determined to be 11 years.

9 In addition, the result of the economic analysis on the campus-wide PV system at UNH
10 suggests that the project is profitable since PI is larger than 1.0. The NPV for Celentano Hall PV
11 system is \$81,996, and IRR of 8.74% is well over the discounted rate of 6%, both indicating that
12 the project is profitable.

13 Application of the economic model to other buildings on campus with varying
14 characteristics, roof sizes, and electricity consumption yielded similar results, where all 26
15 buildings analyzed generated a positive cash flow over the lifetime of the system. The payback
16 period calculated for other buildings ranged between 8-12 years.

17 In addition to geography and other environmental factors, state or federal incentives play
18 an important role in current markets for PV systems [59]. For PV installations in CT, such
19 incentives closely affect the payback period of a project and therefore may determine the
20 outcome of the project. Most of the 26 buildings analyzed would qualify for ZREC incentives.
21 The average annual electricity savings from a campus-wide PV installation on building roofs was
22 estimated to be a \$250,000. Total savings of approximately \$6.3 million could be expected over
23 the 25 year design lifetime of the system. These numbers should be evaluated with regards to
24 current expenditures the University has. Energy costs make up a significant portion of the overall
25 university operation expenses, where UNH was spending approximately \$3 million annually for
26 electricity.

27 The conclusion of this research proved the feasibility of PV system installation at UNH
28 with a reasonable payback period given ZREC incentives can be secured for a project. The
29 results of the study together with its economic analysis could be used to assess the feasibility of
30 PV systems at other universities in CT or in neighboring states that share similar climatic
31 characteristics and economic factors.

32 Installing PV systems on campus not only generates renewable energy that is used on-
33 site, thereby reducing building operation expenditures, but also can be used as an effective tool
34 to raise the level of awareness of the greater university community towards renewable energy
35 and towards sustainable efforts in general. Most students in higher education will graduate in a
36 few years and start making decisions on where they live and work. Being exposed to renewable
37 energy inherently during their higher education may alter their perceptions and expectations,
38 therefore generating long term impacts.

39
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44 Services at Celtic Energy, Inc., Chris Lotspeich.

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