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New Building Cladding System Using Independent Tilted BIPV Panels with Battery Storage Capability

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Abstract: In order to meet renewable energy goals in the near future, the deployment of photovoltaic (PV) panels on buildings will dramatically increase. The objective of this paper is to introduce an improved design for PV cladding systems that will greatly contribute to meeting these renewable energy goals. Typically, building-integrated photovoltaic (BIPV) panels are vertically oriented as cladding and they are not coupled with individual storage batteries. The proposed cladding couples a tilted BIPV panel with one or more storage batteries at each building placement. Thus, the tilted BIPV plus battery system is independent of other power generation in the building and it is referred to as a "building perma-power link" (BPPL) cladding element. Each cladding panel is designed as a stand-alone system, which will be useful for installation, operation, and maintenance. The hyper-redundancy of multiple BPPL cladding panels for a typical building significantly enhances its overall energy resiliency. In order to foster manufacturing ease, each individual cladding unit has been designed at tilts of 45° and 60°. An example of a mid-rise building in Seattle, Washington is provided. The degree of building energy resiliency provided through multiple BPPLs is examined.

Keywords: curtain wall system; BIPV; tilt angle; cladding system; energy resilience; renewable power

1. Introduction

Recent technological advances have made the use of building-integrated and building-attached photovoltaic (PV) panels more robust and cost-effective for energy generation, e.g., References [1,2]. Goals in certain regions of the US, such as Washington State, to achieve greater renewable energy generation using solar energy over the next decade can only be met with significantly increased PV surface area exposed to solar radiance. Utility-scale solar arrays require both large tracts of land and adequate transmission facilities for energy delivery. Available tracts of land for array placement and energy delivery are scarce. Transmission lines are expensive to build and maintain. Therefore, it is anticipated that any substantial increases in solar energy generation in urban areas will rely on existing buildings with building-integrated PV (BIPV) and building-attached PV (BAPV) placement.

The use of multiple BIPVs and BAPVs with single megawatt (MW) size storage batteries has been advocated for increased operational flexibility and resiliency of renewable building energy resources, e.g., References [3–7]. In addition, research has focused on developing more efficient solar cells that comprise the PV module [5,8,9].

In their study of BIPV- and BIPV-thermal systems, Biyik et al. [10] reviewed the energy generation, efficiency, and performance assessment of various panels. They distinguished building-attached PV with building-integrated PV by stating that the attached panels (such as rooftop arrays) have no direct influence on the building's functionality. The fitness of the BIPV panels was found to be related to



several factors such as durability, maintenance, safety, and environmental issues. One hundred and fifteen research studies were compared in terms of performance indicators such as energy generation, nominal power, and efficiency. Various building integration techniques incorporating ventilation were discussed. It was concluded that both façade and rooftop PV panels were equally common in the research literature. Cell and module designs were the most important factors to consider for power output. A review of grid integration techniques was undertaken. It was concluded that there is a wide range of options for BIPV to increase the development of sustainable buildings.

Attoye et al. [11] investigated the customization of BIPV facades primarily within the context of architectural design. Often, there is a conflict in implementing BIPV for maximum power output while also providing adequate daylight, outdoor ventilation, and outdoor scenery for occupant comfort. Customization of BIPV facades to minimize these conflicts was suggested.

Lovati et al. [2] provided an optimization design tool for implementing BIPV into the early stages of the architectural workflow that would consider the balance between architectural cladding needs and energy generation. They identified an approach to optimize the position of BIPV panels with a single MW size battery storage capacity for a given building. The costs of each unit of the cladding as well as the energy generated are included in the analysis.

Sun et al. [12] investigated the influence of the tilt angle of the BIPV on energy generation. They explored the impacts of azimuth orientations and tilt angles with the combined effects of shading on BIPV energy performance. It was found that the tilt angle made a significant difference, and the optimum tilt angles for different designs varied from 30° to 50°.

The objective of this paper is to introduce an improved design for cladding that enhances the energy resilience of buildings while allowing for desirable architectural features. The main innovation is the simple modular form of a tilted BIPV with coupled storage battery that can be integrated into a building as cladding in the same manner in which glazing is attached as part of a curtain wall system. Because each panel-battery system provides continuous, permanent power delivery independently, it adds redundancy to the energy resiliency of the building. The "perma-power link" is used to designate this BIPV system or "building perma-power link" (BPPL) panel. If *N* panels are provided, then *N* degrees of energy redundancy is provided for the building energy resource, which results in a hyper-redundant system. Essentially, the hyper-redundant BPPL units provide permanent, continuous building power that can replace a portion of the grid-based power delivery.

2. Materials and Methods

2.1. BPPL Panel Composition

Figure 1 illustrates a vertical BPPL panel as integrated into the building cladding. In this figure, a "jumbo-sized" 1.5 m by 2.5 m panel delivers power to the interior of the building as DC (USB-type plug) or AC (3-prong outlet). When the power supply exceeds the consumption, the energy is stored in a battery bank attached to the panel and enclosed in the wall. DC power is used by many appliances and lighting systems. Inverters for AC voltage are common for small W and kW batteries but will result in slight power output reductions. The proposed cladding can be located on the building façade through a wall utilization ratio analysis such as described by Sun et al. [12] so that ample window space to provide daylight is available for occupants. Figure 1 illustrates this type of placement for a corridor in a building.



Figure 1. Illustration of a vertical "building perma-power link" (BPPL) system where the rectangular photovoltaic (PV) panel is part of the façade and the battery is enclosed in the wall with power outlets available inside.

Taking into account the size constraints of the individual cladding panels and the wall space, lithium-ion batteries are proposed for the BPPL cladding. Other batteries such as zinc, e.g., as those discussed in References [3,13], are too large and weigh too much, increasing the dead load of the building. However, there are heat concerns about lithium-ion batteries, so ventilation is a key concern. It is noted that most batteries contain controllers and inverters and provide the DC and AC outputs directly as shown in Figure 2 for a sample battery with the following properties: 300-W 220-Wh inverter with AC outlets and DC USB ports [14]. The battery is lithium ion with dimensions of 201 mm by 201 mm by 79 mm and has a weight of 2.27 kg.



Figure 2. Sample off-the-shelf battery suitable for a BPPL cladding panel system [14].

Even if the batteries are "banked," i.e., connected in series, the electricity output connection will be available, so a one-off or bespoke system is not required and off-the-shelf products are adequate. It is well known that latitude, tilt angle, shadowing, and temperature influence BIPV performance. In the next section, these factors are examined.

2.2.1. Influence of Tilt Angle for a Given Location

The tilt angle of the panel, which is denoted here as β , is the most critical concern for energy generation. Figure 3 illustrates an example of a tilted BIPV with a battery bank in a "wedge" configuration ready to be installed in a building. The vertical dimension is l_v , the horizontal overhang or "bottom" is l_o , and the panel dimension in landscape format is l_p . The section of the wedge on the interior part of the building is similar to a window casement approximately eight centimeters thick to accommodate the battery bank and wall plugs.



Figure 3. Tilted building-integrated PV (BIPV) in a BPPL "wedge" configuration.

In the BPPL wedge, the batteries should be attached to the vertical section of the element of length l_v for structural stability of the cladding element. The bottom of the wedge is designed to have openings for ventilation. The overhang length l_o must be minimal not only to reduce the structural loading on the cantilevered PV panel but also to minimize a shadow effect on panels attached below. The bottom and sides of the wedge are designed to be covered with metal or ceramic plates or screens. Consideration of the outdoor elements should be taken into account, such as insects and dust that may interfere with the PV operation. Although 27° is considered optimal for most locations in western US, a 30° wedge of a typical rectangular panel in landscape format has an overhang l_o that was deemed too long for structural integrity and would require a hefty and expensive vertical support system. A tilt angle less than 45° resembles a shading device or awning cover for the typical panel, which has been studied extensively for window shadow coverings, e.g., Reference [12]. Reducing the panel width to resemble a louvered cluster such as advocated by El-Essawy [15] is certainly possible but may not be appropriate for typical construction. Therefore, tilt angles of 45°, 60°, and 90° (vertical) were chosen for further analysis.

The influence of the tilt angle on a wedge system was assessed for an example building in Seattle, Washington on the University of Washington (UW) campus. Hourly solar radiations were obtained with the software Climate Consultant 6.0 [16] for angles of 45°, 60°, and 90°. The results of the solar radiation for each tilt angle are shown in Figures 4–6. These figures illustrate the radiation per month from sunrise to sunset. A percentage comparison of the surface radiation for three tilts is given in Figure 7. It can be seen that there is a noticeable difference in the amount of power generated throughout the day, with 45° being the best tilt angle from an energy perspective.



Figure 4. Surface radiation (Wh/m²) for a tilt angle of 45° .





 90° Tilted (Vertical) South Facing Surface Radiation (Wh/m²) Night Time 4 - 158 158 - 316 316 - 474 >474 (26%) (7%) (53%) (9%) (6%) 12 a.m. 2 a.m. 4 a.m. 6 a.m. Sunrise 8 a.m. 10 a.m 12 p.m. 2 p.m. 4 p.m. Sunset 6 p.m. 8 p.m. 10 p.m. 12 a.m. Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec





Figure 7. Comparison of surface radiation (Wh/m²) for panels with various tilt angles.

2.2.2. Influence of Azimuth for a Given Location

It is well known that the optimal tilt angle increases with the time of day, e.g., Reference [17]. In terms of azimuth, defined here as the direction in degrees of north, south, east, and west, Rowlands et al. [18] found that there is no significant difference in electrical production of PV panels oriented in a range of 15° west to 15° east of due south, defined as having an azimuth of 180° from the north. Obstructions to solar radiation, on the other hand, may produce losses of available energy [19]. Shading is one example of obstruction.

2.2.3. Influence of Shading

Obviously, shading is a concern when tilted panels are used as some near the top of the building may act as shades for those lower down. In this case, "double" wedge cladding with lower decorative surfaces, which can be customized, are proposed as shown in Figures 8 and 9. Valckenberg et al. [20] found that the use of reflective materials for the lower surface of tilted building cladding can increase the AC yield of panels located lower down on the building. In the next section, an example of the design of the BBPL double wedges for a building located in Seattle, Washington is provided.



Figure 8. Double-wedge BPPL panels installed in a typical façade.



Figure 9. Double wedge formation of cladding to mitigate shadows: When $\beta = \gamma = 45^{\circ}$, the height of the double wedge cladding is $2l_v$.

2.2.4. Influence of Heat Transfer to Building Façade

The heat generated by solar radiation should be evaluated when implementing the BIPV or BPPL systems. As discussed in Reference [21], the performance of PV cells is affected greatly by the operating temperatures and it is essential to remove the accumulated heat from the PV cells to increase efficiency. For BIPV systems, naturally or mechanically ventilated PV façades could be used where an air layer is reserved to cool PV modules and the heated airflow could be reserved for other thermal applications in the building [21,22]. Coolant fluid, such as water, could also be used behind the panel to decrease

the temperature of the panel as presented in Reference [1]. The studies also agreed that adding PV panels to the exterior of the building could provide thermal insulation to the building envelope [1,21]. Experiments conducted by Chiu et al. [23] showed that the thermal performance of ventilated BIPV walls was superior to the reinforced concrete wall by having a lower overall heat-transfer coefficient.

As a newly proposed concept, the thermal performance of BPPL in practice has not been evaluated and is beyond the scope of this paper. However, present ventilation techniques used by BIPV could be adopted by BPPL. As shown in Figure 3, small openings are shown at the bottom of the wedge to increase airflow, while in Figure 9, the side covers for the double-wedge would also have small openings for ventilation purposes.

3. Results

In this section, two design examples are provided. The first is theoretical in which the National Renewable Energy Laboratory (NREL) PVWatts Calculator [24] is used to estimate the power output for the wedges installed on the south-facing wall of a non-laboratory building located on an urban campus setting in Seattle, Washington. The second is empirical, where coupled BAPV plus a battery system was directly connected to small appliances in a campus office to investigate BPPL as a proof of concept.

3.1. Theoretical Design Example of Building BPPL System

The results for the energy capacity of an example campus building for the University of Washington building in Seattle are provided to demonstrate the design process. The building has the layout of Figure 8 with length B = 78 m, height H = 18 m, and width W = 35 m. Previous analyses of energy consumption of on-campus non-laboratory buildings, e.g., Reference [7], showed that the typical lighting demand is around 580 kWh per day. Using the NREL PVWatts Calculator [24], double wedges comprised of 315 W panels, of dimensions $1.575 \times 0.826 \times 0.046$ m, and arranged in landscape format at a tilt angle of 45° on a south-facing wall were investigated. Given the length of the building *B* of 78 m and the horizontal length of the double wedge l'_p of 1.575 m and assuming smaller size windows (with a width of $0.5l'_p = 0.79$ m) in between the double wedge columns compared to the windows shown in Figure 8, it was found that 32 columns of the double wedge laddings can be fitted to the south-facing wall. An initial design would provide twelve of the double wedges for each column including the first floor. In total, 384 of the 315 W panels could be mounted, and they would be able to provide monthly AC output from 5669 to 16307 kWh as given in Table 1.

| Month | Solar Radiation (kWh/m ² /day) | Plane of Array Irradiance (W/m ²) | DC Array Output (kWh) | AC System Output (kWh) |
|-----------|----------------------------------------------|--------------------------------------------------|--------------------------|---------------------------|
| January | 1.97 | 61.06 | 6259.27 | 5937.48 |
| February | 3.07 | 86.01 | 8788.46 | 8377.61 |
| March | 3.67 | 113.78 | 11,262.41 | 10,743.08 |
| April | 5.07 | 152.11 | 14,657.31 | 14,012.82 |
| May | 5.04 | 156.14 | 15,010.70 | 14,330.38 |
| June | 5.54 | 166.19 | 15,655.37 | 14,946.10 |
| July | 6.04 | 187.39 | 17,058.86 | 16,307.45 |
| August | 5.99 | 185.62 | 16,836.78 | 16,108.98 |
| September | 5.16 | 154.73 | 14,420.80 | 13,801.30 |
| Öctober | 3.38 | 104.76 | 10,185.72 | 9717.67 |
| November | 2.40 | 72.12 | 7317.39 | 6965.36 |
| December | 1.85 | 57.43 | 5969.96 | 5669.20 |
| Total | 49.18 | 1497.34 | 143423.04 | 136917.41 |
| | | | | |

Table 1. The solar energy output of 384 of the 315 W BPPL panels with a 45° tilt and southern exposure in Seattle using NREL PVWatts Calculator [24].

On a sample day in summer (June 22 was selected), Figure 10 shows that, during daylight hours, the additional power generated by the PV panels would be stored for use during the non-daylight hours. The energy generated represents the estimated energy consumption for the lighting of 580 kWh/day or 17 percent of the total energy consumption for the entire building.



Figure 10. Electricity consumption for lighting and DC/AC output for 384 panels in an example non-laboratory building on the University of Washington (UW) campus.

The results of this simple example show that using the BPPL cladding on one south-facing wall with windows interspersed would provide the electricity needed for lighting continuously without the grid, that is, without being wired into the entire building power supply. During the daylight hours (8 a.m. to 5 p.m.), the panels generated 286 kWh more than what was required for the lighting system. With the built-in battery storage, the excessive amount of energy would be used to power the lighting system during non-daylight hours. The BPPL cladding is supplemental to the grid and would reduce the grid usage. The supplemental nature of the BPPL adds redundancy. In Section 3.3, the influence of multiple BPPL elements on the energy resiliency of the entire building is examined.

3.2. Empirical Design Example

In 2017, a proof-of-concept system was set up in a faculty office in a campus building. The system consisted of four Goal Zero Boulder 100 W PV panels [25] (with a fixed 43° tilt) and a Goal Zero Yeti 1425 Wh storage battery [26]. It is noted that the storage battery also includes an AC inverter and a charge controller. Multiple appliances typical for office use were connected to the system through the built-in AC port on the YETI battery. The detailed configuration of the system is shown in Figure 11.

In this system, power output during daylight hours was used by the appliances, with any additional power being stored in the battery for use during nighttime similar to the theoretical system shown in Figure 10. To estimate the energy demand of a typical office, the energy consumption of the connected appliances was recorded by a smart power strip during a 3-h measurement period when all of them were in use. It was estimated that 121 Wh of energy was needed to support the usage of all the appliances each hour. The hourly energy production of the PV panels was recorded on December 23, 2017 (winter) and July 18, 2018 (summer). It can be seen from Figure 12 that the energy generated from the PV panels could support the usage of all the appliances for at least five hours on a sunny winter day as well as a partly cloudy summer day. The excessive amount of energy stored in the battery could be used to power the appliances during early morning or late afternoon hours.



Figure 11. Configuration of the proof-of-concept-coupled PV panels and battery system: Note that the "battery" also includes an AC inverter and a charge controller.



Figure 12. Energy production and demand of the proof-of-concept experiment in a private office.

Although this configuration differs from the tilted BIPV cladding investigated in the theoretical section, it is used to show that on-site power generation and storage for building occupant use is possible. This empirical model also provides insight into the amount of energy that must be generated and stored for individual offices to be feasible for widespread implementation into buildings.

3.3. Theoretical Analysis of the Effect of Multiple BPPL on the Overall Energy Resilience of a Building

The proposed energy resilience framework for BPPL power allocation uses a bottom-up approach to power support as opposed to a top-down one. In the typical energy-resilience scheme, the building is modeled as a "node" of the power-delivery network also known as "the grid." Decisions about the power delivery and response to disruptions are made by the operators and managers of the network,

within the confines of government regulation, e.g., in the US, the State Public Service Commission or Public Utilities Commission.

Infrastructure resilience is often numerically modeled as a time series describing the inoperability X(t) of systems such as electric power delivery, telecommunications, and water supply and treatment, e.g., References [27,28]. Bruneau et al.'s [29] formulation of "resilience" analysis, which delineates four dimensions as "robustness," "redundancy," "rapidity," and "resourcefulness," is used here to illustrate how energy generation and storage on-site may significantly increase the energy robustness of individual buildings.

The left-hand side plot of Figure 13 shows a time series of power inoperability over time t, denoted by X(t), for a community after the landfall of a hurricane. In this formulation, X(t) = 0% is a fully functional grid and X(t) = 100% represents a fully inoperable or nonfunctional grid. The maximum X(t) value frequently occurs at the time of the disruption, such as hurricane landfall, and is called the "fragility," usually denoted as X_0 . Reed et al. [28] have characterized numerically the inoperability X(t), fragility X_0 , and time to restoration t_r for hurricanes, winter storms, and earthquakes for various locations. Its mathematical representation is discussed in detail in References [28,30].



Figure 13. Inoperability function at the community and building levels.

In the right-hand side of Figure 13, the inoperability X(t) of a typical building that is completely dependent on the grid is shown. Some backup power is assumed for the building, but it does not last for the entire duration of the event and the inoperability reaches 100%. In the proposed energy resilience framework, a BPPL-clad building is much less likely to reach $X_0 = 100\%$ when the grid goes down.

Figure 14 illustrates the effect of multiple BPPL panels on the inoperability X(t). As shown in Equation (1), the total fragility $(X_0)_{\text{building}}$ is given by contributions from the grid, $(X_0)_{\text{grid}}$, and the BPPL panels, $(X_0)_{\text{BPPL}}$.

$$(X_0)_{\text{building}} = (X_0)_{\text{grid}} + (X_0)_{\text{BPPL}} \tag{1}$$

Equation (1) can be expanded to investigate the robustness of the building energy supply for various scenarios. For purposes of illustration, assume $(X_0)_{grid} = 85\%$ and $(X_0)_{BPPL} = 15\%$. If the grid goes down, then the maximum amount of power remaining within the building is 100% - 85% = 15%. That is, it is highly unlikely that all BPPL panels will stop functioning. In order to evaluate the possibilities, a reliability approach is undertaken.



Figure 14. Fragility of energy supply in buildings with BPPL.

For a multistory building with hyper-redundant BPPL panels, the energy fragility $(X_0)_{\text{BPPL}}$ is defined as the probability that the on-site energy infrastructure, i.e., the BPPL panels, is functional at desired performance levels during and after disruptions. This fragility can be modeled through a reliability of a *k* out of *n* system [31], assuming that the desired performance levels can be met if and only if at least *k* out of *n* independent BPPL panels can provide power (each panel is an independent system as shown in the drawing in Figure 1). Mathematically, the expected fragility $(X_0)_{\text{BPPL}}$ is equal to one minus the energy reliability and is given by the following equation:

$$(X_0)_{\text{BPPL}} = 1 - (\text{Probability of at least } k \text{ out of } n \text{ BPPLs survive})$$

= $1 - \sum_{i=k}^n \binom{n}{k} R_i^k (1 - R_i)^{n-k}$, (2)

where R_i is the reliability of the *i*th individual BPPL panel.

The reliability of the i^{th} individual panel R_i denotes the probability that the panel survives a disruptive event (i.e., provides power for the building). For example, if each of the 384 BPPL cladding panels in Section 3.1 has a reliability of 75%, then the probability of at least half surviving a disruptive event is given by the following:

Equation (2) holds true when all panels have the same reliability (i.e., $R_i = R_j$ for $i \neq j$). If they are different across panels (e.g., due to different use or hazard conditions), Equation (2) is generalized to the following equation:

$$(X_0)_{\text{BPPL}} = 1 - \left[\sum_{O \subseteq A, |O| \ge k} \prod_{i \in O} R_i \prod_{j \in A - O} (1 - R_j) \right]$$
(4)

where *A* is the set of *n* indices representing all *n* panels and |O| is the cardinality of a subset *O* of *A*, which represents the set of indices for all operational panels. That is, |O| represents the number of |A| panels that are operational. Assuming different reliabilities across panels, a Monte Carlo simulation experiment was conducted to study the reliability of the example BPPL system in Section 3.1 as follows:

in each replication, R_i (i = 1, 2, ..., 384) was generated from the Beta distribution with a mean of 0.75 and a standard deviation of 0.15 and each panel's survival of a disruptive event was determined as a Bernoulli trial with respective survival probabilities R_i . The simulation was replicated 10,000 times for the fixed k = 192 (i.e., desired performance levels require at least half of the panels to survive a disruptive event). In every replication of the Monte Carlo simulation experiment, the example BPPL system met the desired performance levels (288 panels survived on average with a standard deviation of 8.5).

Both Equations (2) and (4) (for identical and nonidentical panels, respectively) mathematically quantify the effect of hyper-redundancy on a building's energy reliability and affirm that as n increases (i.e., more BPPL cladding panels are installed) while k is fixed (i.e., only k panels are needed to meet the building's desired performance levels), the energy reliability of the building rapidly increases. The reliability (i.e., one minus the expected fragility) is plotted for different k (12, 96, and 192) and $n \ge k$ in Figure 15 to demonstrate the rapid increase of reliability as the redundancy represented by n increases. Energy reliability of a building improves rapidly as n (the number of BPPL cladding panels with individual reliability of 75%) increases for any fixed k.



Figure 15. Comparison of the building BPPL-dependent energy reliability for various *k* values.

From Equation (1), it can be seen that the reliability in Figure 15 is only relevant for the portion of the energy generated through BPPL. It can be seen that the hyper-redundant nature of the systems is creating a "grid" out of the building itself. This concept may be extended to the neighborhood level as well. For example, if there is a cluster of buildings with BPPL cladding and the grid goes down, then the probability of at least k out of n total buildings in that cluster having minimal operating power could be significant. This framework allows for the inclusion of BPPL during disruptions and for greater control by the occupants during and post disruption. The implications of this ability for communities to carry on and adapt, albeit in reduced terms, are discussed in the next section.

4. Discussion

Power continuity in communities has profound implications for inhabitants since they spend 90% of their time in buildings. In this section, the advantages and disadvantages of the BPPL approach are discussed.

The benefits of the BPPL approach are primarily related to the health and well-being of the occupants and, ultimately, of the inhabitants of the community. Improved resiliency and sustainability are by-products of the cladding systems. As shown in Figure 16, "building support services" is

one of approximately one dozen interdependent physical or "gray" systems that comprise the civil infrastructure, e.g., References [29,32].



Figure 16. Building support services as part of the civil infrastructure.

The networked systems of the left-hand side of Figure 16 are interdependent, mostly upon the so-called big three of power, transportation, and utilities such as water supply and treatment. These systems overlap with the following ten community functioning domains developed by Kirsch et al. [33] and Links et al. [34]: (1) communication, (2) economy, (3) education, (4) food and water, (5) government, (6) housing, (7) health care and public health, (8) nurturing and care, (9) transportation, and (10) well-being. Many of the services of the ten domains require specific physical infrastructure such as power delivery [34]. Therefore, the greater reliability of uninterrupted power in buildings will greatly benefit communities. Additionally, the social and economic costs of prolonged power disruptions can be devastating, e.g., Reference [35], and it is anticipated that the BPPL systems would prevent these kinds of tragedies.

Research has shown that occupants greatly value control of their indoor environment, e.g., References [36–38]. Scientific evidence has demonstrated that aspects of workplace design such as lighting, floor plans, and aspects of green technology and architecture can be linked to desirable work outcomes, such as job performance of employees. Moreover, an emerging theme in this area of inquiry is the importance of autonomy; workspace design features that allow for employee choice are more likely to result in enhanced attitudinal and productivity outcomes. According to self-determination theory, autonomy (i.e., having control over one's experiences/behaviors) is essential for motivation and, ultimately, well-being [39]. For example, lighting quality positively predicts productivity, motivation, and work satisfaction, and employees report preferring to have control over the amount of lighting in their immediate workspaces [40–42]. In addition, Huizenga et al. [43] revealed that personal control over environmental conditions has a significant positive impact on occupant satisfaction. Conversely, when employees or occupants are not provided with the opportunity to control important aspects of their indoor environment, it has been shown that stress levels increase [44].

Unfortunately, it is difficult to create one set of indoor conditions that will satisfy all occupants [45]. One of the advantages to the decentralized power supply is that it may allow for more autonomous indoor environment quality controls such as temperature and lighting. At the community level, the greater the decentralization of power supply, the greater the control the individual inhabitants may exercise. This has implications for public policies regarding and the economics of electric power delivery.

In addition, the independent nature of the BPPL system means that cyber-security concerns of the power grid will not substantially affect the building. That is, cyber hacks of the grid operating systems will not affect the distributed energy BPPL resource.

The primary disadvantages of BPPL panels include the risk of fire; costs, both capital and maintenance; and the ramifications of dispersed political and economic power. It is well known that batteries can be fire hazards. In particular, fires related to lithium-ion batteries have been reported for aerospace and mechanical applications, e.g., Reference [46], but have not prevented their use, i.e., been withdrawn from the market. Proper ventilation of lithium-ion batteries is assumed to be the key to fire reduction.

Infrastructure services always come with a cost. Utilities can be public or private, with the latter in business to make a profit. Therefore, the majority of the capital costs in the foreseeable future will be borne by the building owner. The capital cost of the BPPL cladding can be predicted by combining the costs of panels and batteries. For example, assume that four high-efficiency Sunpower X-Series 345 W panels plus a 3-kWh battery would cost about \$6000. Using the Seattle City Light residential cost of power at approximately 8 cents per kWh, the breakeven point would be about twenty years, which is prohibitively expensive for the average consumer. However, it is also noted that many consumers of Seattle City Light elect to pay extra fees for green power sources. In 2018, the flat fee charged for a typical resident was \$24 per quarter. If the green cost is included in the calculations, the payback period is shorter. It is noted that the capital costs of fabricating multiple BPPL panels should be less expensive as the number of units increases. However, the cladding not only is for energy generation and storage but also serves the function of structural cladding. In this regard, the price becomes more reasonable for the dual role.

In addition to the capital costs, the life-cycle costs of buildings include an analysis of the structural integrity for natural hazards. It is not unusual for commercial buildings to have renovations once every 8 to 10 years in the US. If the structural systems are renovated and other aspects are continually maintained and upgraded, it seems reasonable that energy system updates should become more common in the future. Over the lifetime of a building, the replacement of the cladding is expected. If the cladding comes with a power benefit, then the renovation is significantly enhanced.

Decision-making about sustainability and green infrastructure spans a vast literature and is beyond the scope of the paper. In general, it has been established that consumers make decisions about sustainability in ways that are more than solely economic, e.g., References [47,48]. That is, the cost is only one factor among many in determining the decision to live a greener lifestyle.

As mentioned previously, California has passed legislation to reach 100% renewable energy by 2045 [49]. This has broad implications for power companies. Wind turbines and solar farms for densely populated areas require vast footprints and remove large tracts of land from other uses, such as farming. The associated transmission lines required to feed power to meet demand also requires a large swath of land for towers, substations, and related equipment. The footprint associated with PV panels can be easily implemented through existing urban areas if the rooftop and cladding of buildings and other structures are used. Another benefit of the on-site generation is the removal of the transmission portion of the overall delivery scheme as it is well known that transmission losses over long power lines can be quite high, e.g., Reference [50]. However, the economics of this hyper-redundant distribution is uncertain. If the building owners can produce their own (green) power, then they are less likely to purchase it from outside companies. The economic disruption of power generation and delivery has been the focus of much research in the business community. Regardless of the outcome, massive deployment of renewables is going to have a broad impact on the nature of US society as the shift in power delivery from a commodity to a public service occurs.

5. Conclusions

In this paper, a new type of building cladding comprised of BIPV coupled with storage batteries called BPPL cladding has been introduced. A theoretical analysis to estimate the power generation and

storage capabilities of double-wedge-type cladding was undertaken for a non-laboratory building on the University of Washington campus using the NREL PVWatts Calculator [24]. An empirical analysis using coupled PV panels and a commercially available 1425-Wh battery system successfully showed that the system would be able to provide adequate power for office appliances. The specific findings of these investigations are as follows:

- 1. A simple panel plus battery configuration experiment for office appliances in a campus building showed that the configuration provided adequate power independent of the power grid.
- 2. Theoretical analysis of wedge configurations of inclined panels for 47 degrees north latitude was used to examine tilt angles of 45°, 60°, and 90°. The tilt angle of 45° provided the best energy output.
- 3. Double-wedge configurations are useful for cladding placement as well as for preventing shadowing effects. Custom reflection covers for lower wedge surfaces allow for enhanced solar radiation over lower panel surfaces.
- 4. Small openings in the side covers and bottom of the wedge allow for ventilation, which may be important for the higher temperature of the summer season.
- 5. Power output and storage of the BPPL wedges are independent of the grid and supplement the building power supply. They also add robustness and redundancy to the building energy resilience. The increase in resiliency depends upon the amount of generated power available and the degrees of redundancy provided. For example, each double wedge was assumed to power lighting for one office over a 24-h period. The lighting demand was assumed to be 17% of the total power consumed by the building.
- 6. The advantages and disadvantages of the proposed cladding were discussed. The primary advantages are the ability to supplement the building energy continuously and permanently through renewable sources while also providing a barrier to outside elements (cladding). The primary disadvantage is the capital cost required for initial implementation.

In summary, the wedge and double-wedge BPPL cladding configurations hold great promise for advancing green buildings to meet sustainability goals for the future. Ongoing research into the manufacturing capability is presently underway.

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