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Solar Architecture in Energy Engineering

Alexandre Pavlovski

Green Power Labs, Dartmouth, NS B2Y4M9, Canada; ampavlovski@greenpowerlabs.com; Tel.: +1-902-466-6475

Definition: Solar Architecture represents the confluence of the two disciplines of energy engineering and architecture. The concept of Solar Architecture defines a decision-making process to select, design, deploy, and operate solar energy-enabled solutions for environments where solar energy resources are part of the energy mix. The principles of Solar Architecture include maximizing solar energy harvesting from solution's surfaces with a positive balance of energy, carbon, and cost provided by the solution. Solar Architecture application selection is built on two major cornerstones, features and groups, defining the best options in energy engineering of a solar solution. Solar surfaces are key to solar architecture. They are the "heart", and balance-of-system components are the "muscles" of solar solutions. Addressing energy losses in photovoltaic, solar to thermal, and solar to chemical energy conversion allows for increasing energy harvesting yield. Life Cycle Assessment and solar energy harvesting methodologies based on solar surface characteristics define Solar Architecture Balance. This balance allows for defining energy, carbon, and cost return on investment for solar solutions and selecting the best solution for related assets/environment.

Keywords: solar architecture; energy engineering; solar solution; application category; application group; solar surface; energy conversion; energy harvesting; energy losses; solar irradiation; life cycle assessment; balance; carbon; cost; return on investment

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1. Introduction

This Solar Architecture guide describes the practice of efficiently and productively harnessing the main source of external energy supplying our planet, solar energy. Solar energy is vital to life on Earth, accessible to everybody, and transformable to other key sources of energy such as electrical, thermal or chemical.

To harvest solar energy, sunlight must strike a surface. We are surrounded by these surfaces in the built and natural environment.

Optimized "solar surfaces" are always well organized. In the natural world, photosynthetic plants are the most sophisticated practitioners of solar architecture. In the built environment, there are more challenges in achieving both practical and beautiful solutions. As Vitruvius famously said, one must strive to achieve "firmness, commodity, and delight".

Energy engineers know that "solar surfaces" are essential to energy harvesting but not the only part of it. Solar energy harvesting is provided by a "system" in which solar surfaces are the core. Depending on the nature of an engineering solution, the balance-of-system components may differ from each other and vary from application to application.

This guide describes how Solar Architecture in Energy Engineering enables solar energy harvesting.

1.1. History

Energy engineering is one of the emerging engineering disciplines, based on energy sustainability and involving energy efficiency and clean energy concepts for and approaches to any environment.

We believe that energy engineers were among the first to recognize the value and importance of energy in our environments, and our ability to use and leverage energy in our lives. They led the engineering community in its understanding of the importance of solar energy, and of the tools for solar energy conversion into electricity and thermal energy with its further use in thermochemical and thermodynamic applications.

The history of moving solar energy into the mainstream of engineering practices is well known.

Solar energy has been recognized and used through many centuries of human history. In early settlements around the world, the Sun has typically been a key factor in the design and construction of indigenous buildings.

However, the first large-scale energy engineering attempt was successfully achieved in space in the 1960s and 1970s by spacecraft [1,2].

The leadership of energy engineers has had a practical result: practices "in space" through designing, building, and launching spacecraft led to practices "on Earth", and advancements in materials and costs allowed for mainstreaming solar solutions.

Solar energy harvesting achievements through thinking and sharing were merged with leadership, knowledge, and skill in architecture, the art and technique of designing and building [3]. In the energy crisis of 1970s, architects took the "relay race baton" in Solar Architecture passed to them by the minds of engineers. An example in Canada is The Ark, a 1970s experiment in sustainable living in Prince Edward Island, PEI [4].

Sustainable architecture thinking continued to grow. The visions, concepts, and strategies of Solar Architecture demonstrating an approach to "change the face of architecture" [5] and expressing "in built form ... a new direction in the development of mankind" [6] started being publicly discussed by building architects and engineers in the very early 21st century.

Establishing the Solar Architecture approach as "the basis for all buildings" was seen as an immediate transition in practices that would allow clean energy planning, development, and operations to be integrated in new and existing buildings.

As solar energy use in buildings became better understood by its users, solar engineers helped utilities to catch up in the 2000s and 2010s. This brought to action utility-scale solar power plants and defined opportunities for commercial and residential rooftop solar power generation solutions. Energy engineers also worked with urban planners to promote and create urban photovoltaic [7] and rural agrivoltaic [8] landscapes.

These achievements in the 2010s and 2020s have been extended to much broader areas: advanced exterior and interior building envelopes, residential microgrids and grid-interactive efficient buildings, electric mobility and its charging infrastructure—all enabled with solar energy resources and energy-engineered. These practices also contributed to new solar energy standards for open outdoor spaces and landscapes.

Today, we apply our energy engineering knowledge and skills to every existing aspect of solar energy in our daily lives.

1.2. Solar Architecture Principles

The Solar Architecture approach and vision is built on a key junction of two fields of activity: energy engineering and architecture.

Energy Engineering, based on principles of sustainability, is an increasingly critical discipline as humanity grapples with the transition from fossil fuels to renewables. Solar energy engineering is becoming one of the key engineering endeavors to negotiate that transition.

Architecture is the process and the product of planning, designing, constructing, and operating solutions [9]. Initially involving buildings, landscapes, urban design, and naval and seismic applications, architecture evolved in many modern techniques or fields for structuring abstractions in system engineering [10].

The "Solar Architecture" vision addresses solutions with embedded solar energy harvesting built on "solar surfaces" and bringing solar energy resources.

The guiding Solar Architecture Principles supporting this vision are defined as follows:

➢ Maximize solar energy harvesting on solution's surfaces.

➢ Maximize positive energy, carbon, and cost balance in solution's life cycle.

1.3. Definitions

The following definitions are used in this guide.

Energy Resources:

Energy resources are resources for the continuous provision of energy through energy generation, transmission, distribution, storage, and consumption chain.

Solar energy resources are resources available for continuous provision of solar energy through chemical, thermal, or photovoltaic energy transformation.

Energy Harvesting:

Energy harvesting is the process by which energy is extracted in an environment from sources such as solar energy, wind energy, tidal energy, etc.

Solar energy harvesting is the process of extraction of energy by solar energy resources such as photovoltaic, concentrated solar, or thermal solar resources.

Solution:

Energy-enabled solution is a solution for providing energy resource mix for built, industrial, and entertainment environments.

Solar energy-enabled solution (solar solution) is a solution for providing energy resources for environments where solar energy resources are part of the energy mix.

Energy Engineering Practice:

Energy engineering practice includes:

- Selecting and comparing solution options for energy resources;
- Choosing the best option in terms of energy resources, their use, cost, and carbon footprint; and
- Deploying and maintaining the use of the chosen energy resource mix.

Sustainable energy engineering practice:

- Selects and compares solution options for energy resources where renewable energy is a growing and preferably—a dominating resource in the energy mix; and
- Minimizes the use, cost, and carbon footprint of the energy mix.

Solar energy engineering practice is focused on:

- Selecting and comparing solution options for solar energy resources; and
- Deploying and maintaining the use of solar energy resources.

Sustainable Architecture:

Sustainable architecture minimizes harmful impacts to communities and the ecosystem at large through "improved efficiency and moderation in the use of materials and energy" [11].

Solar Architecture is a sustainable system architecture addressing solar energy harvesting capability embedded in solar solutions.

Solar Architecture Balance:

Solar architecture balance is a set of Solar Architecture metrics. It includes:

- Energy balance—the difference between solar energy harvested by the solution (the energy absorbed by the solution's solar harvesting surfaces over its life cycle) and energy embedded in a solution;
- Carbon balance—the difference between carbon saved (the carbon dioxide not emitted by a solution or an environment the solution is a part of due to the solution's operations during its life cycle) and carbon embedded in the solution; and
- Cost balance—the difference between the saved cost of energy (the cost that would be paid to a utility/energy service provider should the solution not use solar energy harvested by the solution in its operations over the life cycle) and the cost of the solution components and operations.

Life Cycle Assessment:

Life Cycle Assessment (LCA) is an analysis technique to assess environmental impacts of a product over the entire period of its life.

Period of Use:

The period of use is defined by the solution's durability (the ability to last over time, resisting wear, breakage, deterioration, etc.) during its life cycle.

Decision-making:

Decision making is a process ensuring the best solar solution selection.

Using the above definitions, this guide describes Solar Architecture in Energy Engineering as a decision-making process to select, design, deploy, and operate solar energy-enabled solutions. It starts with choosing solar solutions applicable to a set of assets in a target environment; defines solar surfaces and related energy harvesting technologies; assesses energy, carbon, and cost balance over the life cycle of these solutions; and completes with final decisions on the best solution option selected.

2. Methods and Applications

Solar Architecture methodologies for energy engineers include three major groups: categories- and applications-related, solar surface-related, and Life-Cycle Assessment-related.

The major objective of applying these methodologies is enhanced decision making on the selection, design, deployment, and operation of a solar solution over its life cycle.

2.1. Solar Architecture Applications Methodology

Solar Architecture applications methodology is built on two major cornerstones: features and groups.

The core application features include spatial, temporal, mobile, transferable (via active and passive energy chains), material, and social categories.

The core application groups include buildings, outdoor spaces, solar farms, solar landscapes, solar transportation, and spacecraft.

Solar Architecture practice uses application features and groups to define the best options in energy engineering of a solar solution.

2.1.1. Application Features

Major features include the following spatial, temporal, mobile, transferable (through active or passive energy chains), material (through PV, construction, and device materials), and social categories:

- SPATIAL
    - Land vs. water
    - Urban vs. rural
    - Highway (controlled-access/limited-access) vs. arterial/collector road vs. local road
    - Onsite vs. remote
- TEMPORAL *
    - Short-term (e.g., "minute, hour or day") vs. mid-term (e.g., "month or year") vs. long-term (e.g., multi-year) (* temporal category defines operational requirements in solar energy management)
- MOBILE
    - Moving vs. stationary
    - Civil vs. military
- TRANSFERABLE
    - Active energy chain (harvesting (e.g., "solar power generation")/transmission/distribution/storage/consumption) vs. passive energy chain (harvesting/storage/consumption)
    - Grid-connected vs. near-grid vs. off-grid

- MATERIAL
    - PV: crystalline/thin-film/organic
    - Construction: wood/stone/concrete/glass/metal/coating/asphalt shingle/sand/soil/plant
    - Device: metal/semiconductor/plastic/liquid
- SOCIAL
    - Aesthetic
    - Social impact

2.1.2. Application Groups

Typical solution application groups include buildings, outdoor spaces, solar farms, solar landscapes, and solar-powered vehicles, and comprise the following application subgroups:

- SOLAR BUILDINGS
    - External envelope
        - Building-applied photovoltaics (BAPV)
        - Building-integrated photovoltaics (BIPV)
    - Internal envelope
        - Organic PV energy harvesting
    - Solar water heating
        - Domestic water heating
        - In-floor water heating
- SOLAR OUTDOOR SPACES
    - Solar street lighting
    - Solar campuses
    - Solar parks
    - Solar carports/canopies
    - Solar parking ticket machines
    - Solar digital advertising screens and billboards
- SOLAR FARMS
    - Utility scale
    - Community solar
    - Rooftop PV
- SOLAR LANSCAPES
    - Photovoltaic
    - Agrivoltaic
    - Landscape lighting
- SOLAR-POWERED VEHICLES
    - Land vehicles (e.g., solar-powered EV) and infrastructure (e.g., solar charging EV stations, solar traffic signs, etc.)
    - Marine vehicles (e.g., solar ferries) and infrastructure (e.g., solar buoys)
    - Aerial vehicles (e.g., solar-powered planes) and infrastructure (e.g., solar runway and taxiway signs, terminals, etc.)
    - Space vehicles (e.g., spacecraft such as communications, Earth observation, meteorology and navigation satellites, etc.) and infrastructure

2.1.3. Solar Architecture Table

Based on application features and groups for a solution, the best solution options are selected for energy engineering. The Solar Architecture Table reviews and considers possible options in selecting and engineering solutions. A table template defining the features of a solution to be reviewed at a high level is shown in Table 1.

Table 1. Solar Architecture Table template.

Application Features	Solar Buildings	Solar Outdoor Spaces	Solar Farms	Solar Landscapes	Solar-Powered Vehicles
Spatial					
Temporal					
Mobile					
Transferable					
Material					
Social					

The Solar Architecture Table may also be used for solar harvesting to add new solution categories and applications in energy engineering and provide solution selection and design.

Examples of solar solution options are shown in Figure 1.

Solar Buildings—External Envelope: BAPV—Roof

Credits: © CanmetENERGY—Varennes)

Solar Buildings—External Envelope: BIPV—Wall

Credits: © Fraunhofer ISE

Solar Buildings—External Envelope: BIPV organic—Wall

Credits: © Laurits Jensen

Outdoor Spaces—Solar Street Lighting

Credits: © IndiaMart

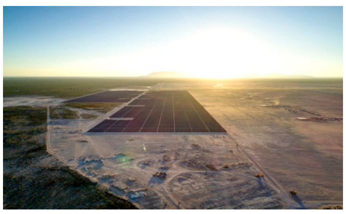
Outdoor—Solar Traffic Signs

Credits: © Indore Municipal Corporation

Solar Transportation—EV Infrastructure

Credits: © Beam Global

Solar Farms: Utility-Scale PV



Credits: Secretaría de Energía/Gobierno de México

Solar Landscapes: Photovoltaic

Credits: © Enrico Cano

Solar Landscapes: Agrivoltaic

Credits: © Akuo Energy

Figure 1. Examples of solar solution options.

An example of the Solar Architecture Table defining and comparing solution options is shown in Appendix A for the solar buildings/external envelope applications group.

2.2. Solar Harvesting Surface Methodologies

Solar Harvesting Surface Methodologies include the means to define and manage solar harvesting surfaces, understand solar irradiation on these surfaces, and access solar irradiation data for these surfaces.

2.2.1. Energy Harvesting Surfaces—The Key to Solar Architecture

The key to solar architecture is surface.

To better appreciate energy engineering, we can paraphrase the statement of David Leatherbarrow and Mohsen Mostafavi in their "Surface Architecture" publication [12]:

> "The properties of an object's surface absorbing sunlight ... are not merely superficial; they construct the spatial effects by which solar architecture communicates. Through its surfaces an object declares both its autonomy and its ability to be energized".

To define any object in energy engineering from a Solar Architecture standpoint, the following statements and definitions are important.

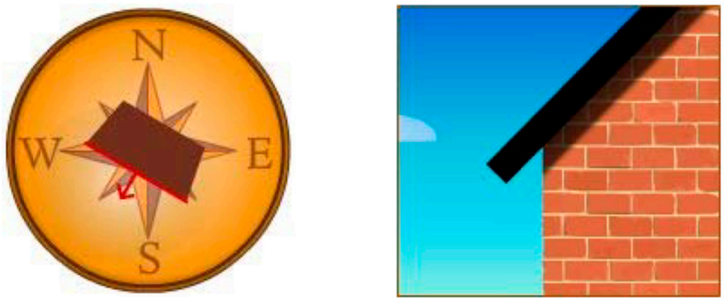
DIVERSITY OF SURFACES

Each object has a number of surfaces, from one (e.g., simple PV module) to many (e.g., walls and roofs of a building)—see Figure 2.

Figure 2. Diversity of surfaces: residential house roof.

SPATIAL DIMENSIONS

- Any surface in 3D space can be described by two spatial properties: tilt and azimuth.
  - For linear surfaces (planes), tilt and azimuth of all the points on the surface is the same (Figure 3).
  - For non-linear (curved) surfaces, the tilts and azimuths of points may be different.
- Every point on the surface has its specific geographic coordinates (e.g., latitude and longitude).
- Any surface has latitude and longitude ranges.



(**a**) (**b**)

Figure 3. Spatial dimensions: (**a**) azimuth and (**b**) tilt.

CONNECTION WITH THE SUN: STATIC OR DYNAMIC

The tilt and azimuth of the Sun in relation to a surface point are changing through time.

Any surface of the object may be static (or stationary) or dynamic. If the surface is static, the surface points have tilt and azimuth defined and not changing. This means that for every surface point, the difference between the tilt and azimuth of the point and the relative tilt and azimuth of the Sun are known at any moment.

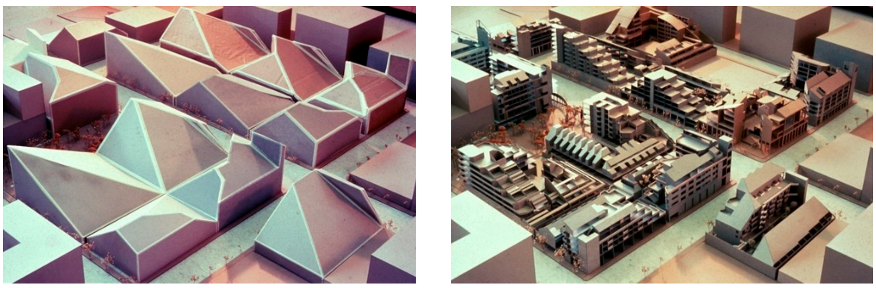
If the surface is dynamic, the tilt and azimuth of any point on this surface will be changing depending on the move of this surface, and the difference between the tilt and azimuth of the point and the relative tilt and azimuth of the Sun have to be calculated for any moment.

OBSTRUCTION OF SUNLIGHT AND SOLAR ENVELOPE

Sunlight incident on a surface may be obstructed by surrounding objects (e.g., a tree, a building, a hill, or a moving truck), which reduces the ability to harvest energy.

The shading effect depends on the nature of the obstructing objects and is generally proportional to the altitude angle to the top of the object and spread of the azimuth angle of the solar path behind the object in relation to the surface point. Note that everything below the surface plane does not produce shading of direct sunlight.

Access to sunlight and the nature of obstruction of sunlight for a set of surfaces are well defined by Ralph Knowles in his solar envelope concepts [13–16] (see Figure 4). "The solar envelope is a construct of space and time: the physical boundaries of surrounding properties and the period of their assured access to sunshine. These two measures, when combined, determine the envelope's final size and shape" [17].



(**a**) (**b**)

Figure 4. Obstruction of sunlight: (**a**) solar envelopes and (**b**) building designs.

ENERGY SINK AND THERMAL MASS

Holding, discharging, or transmitting solar energy imposed on a surface depends on the thermal mass the surface is a part of or connected to, making it an energy sink.

Thermal mass allows for keeping energy in the form of heat or chill, providing "inertia" against temperature fluctuations [18].

The impact of thermal mass of the surface is important for passive or active heating and cooling.

2.2.2. Solar Irradiation on Surfaces: Direct and Diffuse

Solar energy at any object's surface is provided by two key irradiation components: direct and diffuse irradiation. The "direct" irradiation component directly reaches a surface. The "diffuse" irradiation component is scattered by the particles in the atmosphere and is non-directional. The total of these two components reaching the same surface is called global irradiation [19].

The object's surface at each of its surface points absorbs and/or reflects solar energy. Total solar energy absorbed by the surface is a spatial integral of energy absorbed by its surface points.

Solar irradiance refers to the rate of energy received from the Sun per surface unit: W/sq.m. Integrating it spatially over a surface will give solar irradiance for the surface in units of power (e.g., Watts). Integrating it temporally over a period of time provides solar irradiation in units of energy (e.g., Wh or Joules). This spatio-temporal integration is used to define the characteristics of an object or solution's Solar Architecture.

2.2.3. Access to Energy Harvesting Data: Solar Resource Maps

Data on solar irradiation necessary for solar solutions are represented by solar maps. These maps with dedicated spatial resolution may present daily, monthly, and annual solar irradiation averages.

These maps are often presented online in web mapping applications built in Geographic Information System (GIS) environments; these web applications also define spatial and temporal resolution of the maps presented.

Many countries today have public maps and web mapping applications issued at the federal level and covering the whole jurisdiction. These maps are built on solar radiation and meteorological data collected over a long period of time. An example is the National Solar Radiation Data Base (NSRDB) [20]. An open dataset, the current NSRDB provides solar irradiance at a 4 km horizontal resolution for each 30 min interval computed by the National Renewable Energy Laboratory's (NREL's) Physical Solar Model. The data can be freely accessed via NREL's web link [21].

Often, solar resource maps with higher resolution are required for regional (such as state or provincial maps) and municipal (urban solar maps) applications (see Figure 5). These maps may be also available and free to use.

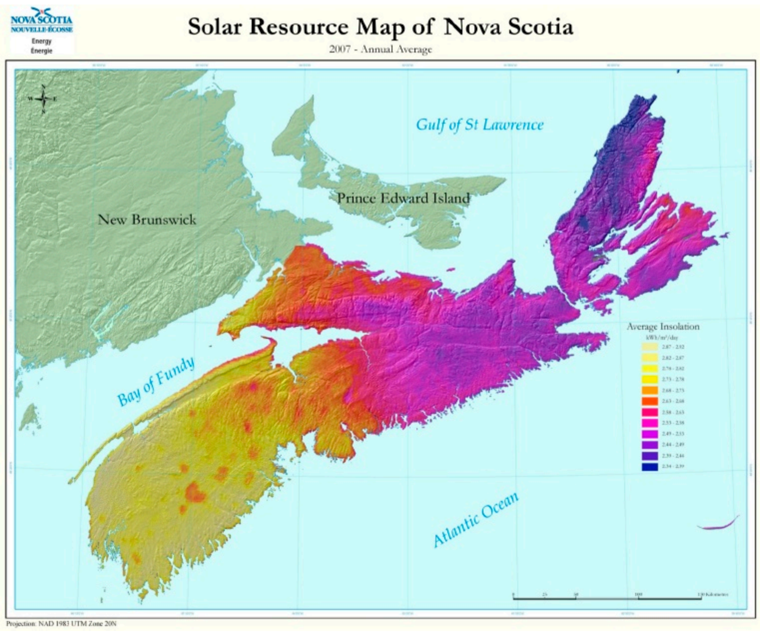


Figure 5. Provincial solar map: Nova Scotia, Canada.

Depending on solar solution applications, solar maps at the community and site level may require higher spatial and temporal resolution and display additional properties required for solar engineering (e.g., global horizontal, direct normal and diffuse irradiation, specific tilt and azimuth, etc.)—see Figure 6.

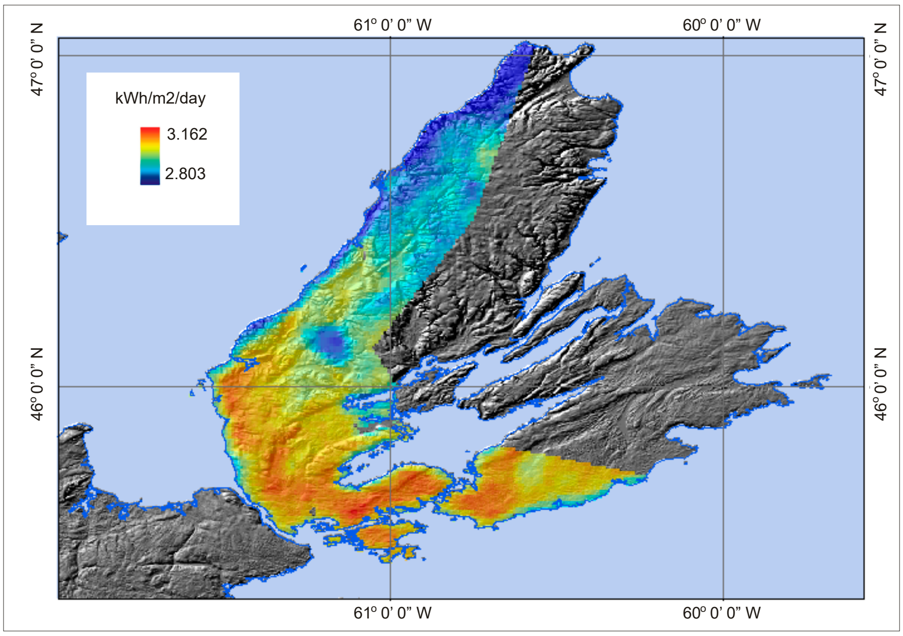


Figure 6. Regional solar map: Strait-Highlands Regional Development Authority.

To inform architects, energy engineers, and their clients on the use of solar solutions, the derivatives of solar resource maps defining solar energy harvesting by solar solutions are added to solar maps. As an example, photovoltaic potential maps (in kWh/kW_{peak} units) are provided.

An example of access to solar resource and solar harvesting technology is the "Photovoltaic potential and solar resource maps of Canada" web mapping application [22]. This application gives estimates of photovoltaic potential (in kWh/kW_{peak}) and of the mean daily global irradiation per surface unit for any location in Canada on a 2 km grid.

Another example of access to solar resource and photovoltaic power potential is the Global Solar Atlas provided by the World Bank Group to support the scale-up of solar power in its client countries [23].

An important step in understanding solar resource and its energy generation potential in communities was presented by urban solar maps. These maps describe solar generation potential at building roof resolution and the efficiency of solar technologies used [24].

The initial generation of solar urban maps was based on the analysis of 2D aerial images available from open sources such as Google Maps. These two-dimensional images did not allow for collecting correct data on roof slopes nor provide information on building walls. Additionally, these maps did not allow for automated reconstruction of 3D environments to consider roof-specific obstructions to solar radiation. However, these maps presented important spatial information on the distribution of solar generation potential in communities.

The next generation of urban maps was driven by advances in aerial photo imagery. Better image resolution as well as the use of oblique photography which showed buildings and houses from all sides allowed for manual reconstruction of building structure in 3D. Still, the technology did not allow for automated creation of a 3D model of the city/community and automated processing of obstructions data.

The third and most advanced urban solar mapping was based on airborne LiDAR (Light Detection and Ranging) technology for optical remote sensing. LiDAR measures properties of scattered light to find range and/or other information of a distant target.

Airborne LiDAR data are used to reconstruct a 3D urban environment using digital elevation models of urban areas with high spatial resolution. Using LiDAR-based surface models accounts for surface geometry and allows for precise determination of the impact of obstructions to solar irradiation [25] (see Figure 7).

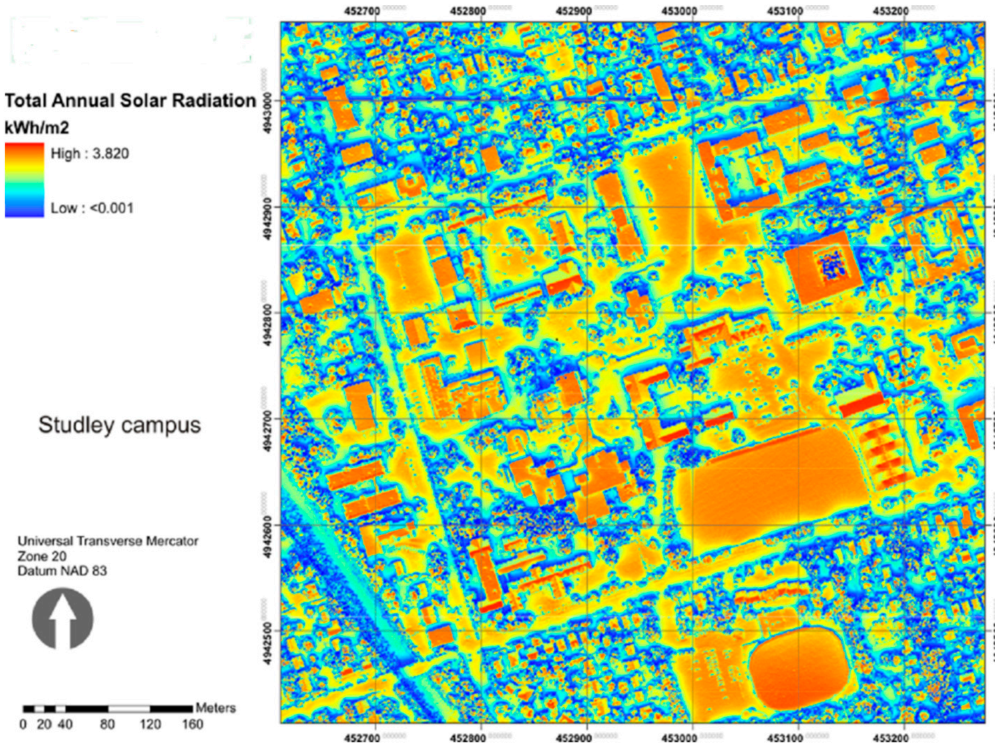


Figure 7. LiDAR-based solar map of Studley campus, Dalhousie University, Halifax, Nova Scotia.

2.3. Solar Energy Conversion and Losses Reduction Methodologies

Energy conversion performance is a critical factor defining energy harvesting in a solar solution. The key indicator defining energy harvesting losses in the solution is the Conversion Performance Ratio (PR). It is defined as the ratio between energy input P_{input} and energy output (energy yield) P_{output} of the solution after harvesting losses have been deducted: PR = P_{output}/P_{input}. PR is also called Total Derate Factor D_{total} as it is defined by the total loss in energy harvesting L_{total}: PR = D_{total} = $1 - L_{total.}$

Losses in the three major areas of solar energy harvesting—photovoltaic, solar to thermal, and solar to chemical energy conversion—and related technological innovation opportunities focused on reducing the losses and increasing the energy harvesting yield are briefly described below.

2.3.1. Photovoltaic Conversion

PV conversion is used in a very broad spectrum of applications ranging from milliwatts to gigawatts in conversion power. Core conversion components include solar cells/modules/arrays, DC/AC inverters, and/or DC/DC converters.

PV conversion losses include optical losses (e.g., incidence angle modifier factor, soiling loss factor), PV conversion losses (e.g., cell efficiency, cell degradation loss, module quality loss, mismatch loss), and DC-related losses (e.g., DC wiring loss, inverter efficiency). Power grid-related applications also include AC-related losses (e.g., AC wiring loss, system auxiliary losses, transmission losses, and system unavailability).

Technology innovation opportunities with PV include new developments in power conversion efficiency of solar cells.

Research and development of high-efficiency crystalline Si solar cells addressed new cell structures. Examples include passivated emitter rear cell, tunnel oxide passivated contact solar cell, interdigitated back contact cell, heterojunction with intrinsic thin-layer cell, and heterojunction solar cells with interdigitated back contacts [26].

New achievements were demonstrated with thin-film solar cells. Commercially produced copper–indium–gallium–selenide (CIGS) cells that have high potential in flexible or multijunction PV applications demonstrated 16.7% efficiency [27].

Perovskite and organic materials achieving efficiencies of conventional silicon solar cells. Recent work demonstrated a power conversion efficiency of 23.6%, approaching that of conventional silicon solar cells. This technological breakthrough paved the way for flexible, light-weight, low-cost, and ultra-thin photovoltaic cells for wide-ranging applications [28].

Other technological advances addressed operating characteristics of solar cells, such as operating temperature essential for photovoltaic conversion. For example, the rapid development of radiation cooling technology brought opportunities for radiation cooling of solar cells [29].

2.3.2. Solar to Thermal Energy Conversion

Solar thermal solutions mostly include concentrating solar power (CSP) generation and solar water/air heating applications. All these applications experience optical and thermal losses in radiative, convective, and conductive heat transfer.

In central receiver-based CSP plants, solar irradiation is concentrated on a tower mounted receiver by the use of large mirrors (heliostats). Heat transport fluid flowing through the receiver tubes is heated up by absorbing the incident energy on the receiver and is used to produce steam which drives a turbine. Energy losses determine receiver efficiency and CSP generation [30].

In collector-based CSP plants with linear Fresnel or parabolic trough collectors, heat transfer fluid is brought to a power generation unit and a thermal energy storage unit. Energy losses determine collector, power generation, and thermal energy storage efficiency [31,32].

Technology innovation opportunities with CSP applications include new developments in particle technologies. Particle-based CSP (Generation 3) will enable higher temperatures (>700 °C) with direct storage for next generation, dispatchable, concentrating solar power, process heating, thermochemistry, and solar fuels production [33,34]. The particle receiver system uses solid particles (ceramic or sand) that are heated directly as they fall through a beam of concentrated sunlight.

Solar water heating is often used for urban and rural applications. The core application components include flat-plate solar collectors (flat-plate or vacuum tube), solar hot water storage tank, water heater, and flow pipe network. Energy losses occur due to heat transfer in collectors [35,36] and to solar hot water recirculation.

Technology innovation opportunities with solar water heating address solar hot water recirculation automation, specifically in multi-unit residential buildings [37].

2.3.3. Solar to Chemical Energy Conversion

Solar chemical solutions cover chemical, electrochemical, and photoelectrochemical and thermochemical areas converting solar energy into hydrogen or other hydrocarbon products such as energy storage media. Photosynthesis is the most sophisticated system of solar-to-chemical energy conversion developed by nature; this solar chemical conversion is currently used for engineered photosynthesis [38].

Technology innovation opportunities are currently focused on efficient and economically attractive thermochemical energy storage (TCES) systems at high temperatures with long-term durability and performance stability [39,40].

Technology advancements in the solar thermochemical area using concentrating solar thermal for industrial decarbonization enable CSP with thermal energy storage to be integrated with high-temperature process technologies to produce economically important products, such as steel, cement, ammonia, and other chemicals and fuels, e.g., used for the decarbonization of the transportation sector [41].

In the engineered photosynthesis area, technology innovation addresses the development of more efficient photosynthesis, along with sustainable and climate-resilient cropping systems to improve both energy and crop yields and crop nutritional value [42].

2.4. Life Cycle Assessment Methodologies for Circular Economy

The Life Cycle Assessment (LCA) methodologies referred to in this guide are inspired by the "cradle-to-cradle" approach in the circular economy [43].

The International Organization for Standardization (ISO) 14040 Environmental Management standard series are recommended for selecting methodologies for Life Cycle Assessment in energy engineering practice [44,45].

2.4.1. Life Cycle Energy Assessment

Life Cycle Energy Assessment involves all energy use components of a solution in its life cycle. These life cycle energy components include embodied energy (energy content of all the materials used in solution including manufacturing and processing, transportation, delivery, and installation), operating energy (energy required for operations, maintenance, and upgrades), and waste disposal energy (energy required to demolish solution and to transport the material to landfill sites and/or recycling plants).

2.4.2. Life Cycle Carbon Assessment

Life Cycle Carbon Assessment involves all energy use components of a solution in its life cycle, and carbon cycle support in product eco-design and operations.

The life cycle carbon components include embodied carbon (energy content of all the materials used in solution, including manufacturing and processing, transportation, delivery, and installation), operating carbon (required for operations, maintenance, and upgrades), and recycling.

2.4.3. Life Cycle Cost Assessment

Life Cycle Cost Assessment involves all the components and operations costs of a solution in its life cycle. These life cycle costs include components' embodied energy cost (cost of all the materials used in solution including manufacturing and processing, transportation, delivery, and installation), operating costs (including costs required for operations, maintenance, and upgrades), and recycling/waste disposal costs (costs required to reuse, repair, refurbish and recycle, and to demolish and transport the material to landfill sites and/or recycling plants).

3. Expected Results and Outcomes

The results and outcomes referred to in this guide are focused on the metrics enabling decision making in selecting and engineering solar solutions.

These metrics define how much energy and carbon were used by the solution options in their life cycles, and what were the costs during this period. The metrics also define how much solar energy was harvested over the life cycle, and what were the carbon and cost savings brought by the solution due to solar energy harvesting. Finally, these metrics define Solar Architecture Balance for each of the reviewed solution options as the difference between energy, carbon, and cost used and saved by these options.

3.1. Solar Architecture Ratios

Solutions' Solar Architecture ratios define relationships between energy, carbon, and cost in the solution's life cycle.

There are two groups of the Solar Architecture ratios:

- Those using Solar Architecture Balance, and based on energy, carbon, and cost; and

- Those using Solar Architecture categories such as life cycle use and energy harvesting, and based on sub-categories such as embodied, operating and waste energy, carbon, and cost.

Solar Architecture Balance ratios and related units are defined as follows:

- Energy-to-Carbon Ratio, kWh/kg CO_2
- Energy Cost Ratio, kWh/\$
- Carbon Cost Ratio, kg CO_2/\$

These ratios allow for comparing solar solutions and support the decision-making process in the initial stages of energy engineering.

Life Cycle Assessment sub-category ratios are defined as follows:

- Embodied-to-operating, embodied-to-waste, and operating-to-waste ratios; and
- Embodied-to-life cycle use, operating-to-life cycle use, and waste-to-life cycle use ratios within the life cycle use category.

Solar energy harvesting sub-categories are defined as follows:

- PV to Solar Thermal, PV to Solar Chemical, Solar Thermal to Solar Chemical; and
- PV to Energy Harvesting, Solar Thermal to Energy Harvesting, Solar Chemical to Energy Harvesting.

3.2. Solar Architecture Scorecards

A Solar Architecture Scorecard is shown in Table 2.

Table 2. Solar Architecture Scorecard template.

Solar Architecture Scorecard	**Period of Use, Years**	**Energy, kWh**	**Carbon, kg CO_2**	**Cost, \$**
Life Cycle Use				
Components				
Raw Material Extraction				
Manufacturing and Processing				
Transportation and Delivery				
Usage and Retail				
Waste Disposal				
Total Life Cycle Use				
Energy Harvesting Yield				
Photovoltaic				
Solar Thermal				
Solar Chemical				
Total Energy Harvesting Yield				
Solar Architecture Balance				

Solar Architecture Balance defines positive or negative values showing how any solution meets the Solar Architecture Principles over its period of use.

Specific LCA characteristics below may be defined per unit of solution surface exposed to the Sun: specific energy, kWh/m^2; specific carbon, kg CO_2/m^2; specific cost, \$/m^2. Other specific Solar Architecture characteristics are defined by specific energy, carbon, and cost to solar irradiation on the solution surface(s) over the period of use (in kWh/m^2): specific energy, %; specific carbon, kg CO_2/kWh; specific cost, $/kWh. Additional metrics such as levelized cost of energy [46] may also be added to solution characteristics.

Existing and in-development LCA reviews for photovoltaic, solar thermal, and solar chemical solutions are recommended for the Solar Architecture Scorecard. As an example, selected LCA reviews for energy conversion components and systems decarbonizing power grids are shown in [47–59].

In PV conversion, the example LCA reviews present a holistic evaluation of different types of PV from traditional silicon-based to innovative non-silicon-based, such as organic PV [47,48]. It also involves concentrating photovoltaic (CPV) cells and modules [49]. Assessment is provided for very large-scale PV systems working in different environments, specifically operating in desert areas [50]. Comparison is made of the energy and environmental profile of PV modules (thin-film and crystalline) and solar thermal collectors (flat plate and vacuum tube) [51], and the LCA of selective flat-plate coatings is explored [52].

In concentrating solar thermal conversion, examples of parabolic trough collector and power tower LCA are presented [53], and key design alternatives for power tower based concentrating solar power systems are reviewed [54]. A comparison of a solar thermal power plant with parabolic trough collectors and a photovoltaic plant with a single-axis tracking system LCA is shown [55].

In solar chemical conversion, Life Cycle Assessments of a concentrating solar power plant in tower configuration with and without thermal energy storage [56] and thermochemical energy storage integration concept examples are presented [57]. An LCA review of microalgal and lignocellulosic bioenergy products from thermochemical processes is also shown as an important example [58]. Overall, environmental and circular economy implications of solar energy in decarbonized grids are summarized [59].

3.3. Return on Investment as an Energy Engineering Driver

3.3.1. Energy Return on Investment

Energy return on investment (EROI) is the ratio of energy delivered from a particular energy resource to energy required to deliver that energy [60].

When the EROI of a source of energy is less than or equal to one, that energy source becomes a net "energy sink" and can no longer be used as a source of energy.

In Solar Architecture practice, "Energy Delivered" is the energy absorbed by a solution's solar harvesting surfaces over its life cycle, and "Energy Required to Deliver that Energy" is the energy used to manufacture and maintain the solutions' components of and embedded technologies in these surfaces over this life cycle.

In an example of Solar Architecture EROI for a stand-alone solar photovoltaic system solution, "energy delivered" is energy generated by a stand-alone solar photovoltaic system over its life cycle (e.g., 25 years or more), and "energy required to deliver that energy" is the energy needed to manufacture, transport, install, and maintain a set of solar PV modules, the mounting system, cables, inverters, transformer, monitoring equipment, and other balance-of-system equipment used over this period of time.

3.3.2. Carbon Return on Investment

Carbon return on investment (CROI), also sometimes called carbon saved on carbon invested, is the ratio of the amount of carbon saved by using a solution through its life cycle operations to the amount of carbon embedded in the components of the solution.

In Solar Architecture practice, "carbon saved" is the carbon dioxide not emitted by a solution or an environment the solution is a part of due to the solution's operations during its life cycle, compared to status quo scenario of operation, and "carbon invested" is the carbon embedded in the solution components.

In an example of Solar Architecture CROI for a stand-alone solar photovoltaic system solution, "carbon saved" is carbon saved by a stand-alone solar photovoltaic system over its life cycle (e.g., 25 years or more) due to its operations as compared to hosting power utility carbon dioxide emissions. "Carbon invested" is the carbon embedded in PV modules, solar inverters, and other balance-of-system equipment. An example includes carbon dioxide emissions embedded at manufacturing crystalline silicon PV components such as poly-Si, ingots, wafers, cells, and modules [61]. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation solutions are adequately presented in this example [62].

3.3.3. Cost Return on Investment

Cost return on investment (ROI) in a solution is a ratio between net income from the solution (over a period) and financial investment in the capital and operation costs of this solution.

In Solar Architecture practice, "net income" is the saved cost of energy that would be paid to a utility/energy service provider should the solution not use the solar energy harvested by the solution in its operations over the life cycle; "investment" is the cost of the solution components in charge of using solar energy in its operations over the life cycle.

In an example of Solar Architecture ROI for a stand-alone solar photovoltaic system solution, "net income" is the saved cost of electricity from a hosting power utility that would be paid to the utility should the solution not use solar energy in its operations over the life cycle. "Investment" is the cost of the solution components (that may include land) purchased to generate solar power in its operations over the life cycle; this includes refurbishing and purchasing additional system components during the PV system life cycle. In this example, solar modules' standard warranty period is 25 years, an average standard warranty period of solar inverters is 10 years, and there may be other balance-of-system components with expected life cycles less than 25 years which will require additional investments during the expected 25-year life cycle period.

3.4. Solar Architecture—Decision-Making

A critical step in energy engineering practice driven by Solar Architecture is decision making. This step ensures that the best solar solution is selected for a client.

While clients' needs and strategies for solar energy use are various, the energy engineering objective must match the Solar Architecture Principles: maximize solar energy harvesting on solution's surfaces while ensuring positive energy, carbon, and cost balance in solution's life cycle.

To achieve this objective, a target share of solar energy in the client's energy mix is defined, and comparisons are made on competing applications across different application groups (e.g., rooftop solar vs. carport solar vs. solar garden) or within the same group (e.g., BAPV vs. BIPV or photovoltaic vs. agrivoltaic landscape)—see Appendix A.

The overall result of this step is the decision made on the winning application(s) to be used for design, deployment, and operations in the client's asset portfolio.

4. Conclusions

Solar Architecture represents the confluence of two disciplines: energy engineering and architecture.

The concept of Solar Architecture defines a decision-making process to select, design, deploy, and operate solar energy-enabled solutions for providing energy resources for environments where solar energy resources are part of the energy mix. It chooses applicable solar solutions, defines solar surfaces and related energy harvesting technologies, assesses energy, carbon, and cost balance over the life cycle of these solutions, and helps making decisions on the best solution options.

The principles of Solar Architecture include maximizing solar energy harvesting from solution's surfaces with a positive balance of energy, carbon, and cost provided by the solution.

Solar Architecture application selection is built on two major cornerstones: features and groups. Solar Architecture practice uses application features and groups to define the best options in energy engineering of a solar solution.

Solar surfaces are key to solar architecture. They are the "heart", and balance-of-system components are the "muscles" of the solution.

Understanding and addressing energy losses in the three major areas of solar energy harvesting—photovoltaic, solar to thermal, and solar to chemical energy conversion—allows for technological innovation to increase energy harvesting yield.

Life Cycle Assessment and solar energy harvesting methodologies based on solar surface characteristics define Solar Architecture Balance. This balance allows energy engineers to define energy, carbon, and cost return on investment for solar solutions applicable to their asset portfolio and to make decisions on selecting the best solution for the assets/environment.

The evolving integration of the energy engineering and architecture disciplines in Solar Architecture supports a future of energy generation and consumption—both elegant and safe, practical and beautiful. It represents one of the most fundamental aspects of a sustainable future for our world.

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Appendix A. Solar Architecture Table Outputs

The guidelines in Appendix A provide recommendations on the Solar Architecture Table outputs supporting energy engineers' decision making on solar solutions.

The three major outputs of the Solar Architecture table are solar surfaces, system components, and energy losses of target solutions. These outputs allow for defining a solution baseline for competing applications and for providing Life Cycle Assessment, solar energy harvesting, and Solar Architecture Balance characteristics. They also allow for addressing harvested energy loss reduction through technological innovations.

An example of the Solar Architecture Table and outputs defining and comparing solution options is shown below.

APPLICATION GROUP: Solar Buildings—External Envelope, competitive solutions compared: Building-applied photovoltaics (BAPV) and Building-integrated photovoltaics (BIPV).

The major outputs of the Solar Architecture Table: Solar Buildings—External Envelope are indicated as follows.

SOLAR SURFACES:

Surface area, azimuth, and tilt for each selected surface:

For BAPV—roof surface area (e.g., 120 m^2), azimuth (e.g., 15 degrees southwest), tilt (e.g., 30 degrees).

For BIPV—wall surface area (e.g., 120 m^2 southwest wall and 60 m^2 southeast wall), azimuth (15 degrees southwest and 75 degrees southeast correspondingly), tilt (e.g., 90 degrees).

Solar envelope: for BAPV/BIPV according to the surrounding built environment (e.g., within 100 m radius).

Table A1. Solar Architecture Table: Solar Buildings—External Envelope (filled cells indicate applied features of the compared solutions).

Solution Features	**GROUP: Solar Buildings—External Envelope**	
CATEGORY:	**Building-Applied Photovoltaics (BAPV)**	**Building-Integrated Photovoltaics (BIPV)**
Spatial		
urban	High-density built environment	High-density built environment
onsite	Roof surface segments	Wall surface segments
Temporal		
short-term	Short-term (hourly) energy changes in PV power generation to maximize solar energy in the building energy mix. May need to optimize/reduce PV power generation to meet utility grid requirements.	Short-term (hourly) energy changes in PV power generation to maximize solar energy in the building energy mix. No limitations in solar power generation.
Mobile		
stationary	Fixed-tilt mount	Fixed-tilt mount
civil	Commercial building	Commercial building
Transferable		
Active energy chain:		
solar generation	Active energy harvesting only through PV power generation	Active energy harvesting through PV power generation
storage		Batter-based electricity storage for PV and for utility time-of-use rates
Passive energy chain:		
harvesting		Passive energy harvesting for heating
grid-connected	Front-of-the-meter (FTM), grid-interactive, may sell ancillary services to grid	
near-grid		Behind-the-meter, temporary connection to grid
Material		
PV:		
crystalline	Monocrystalline silicon (c-Si)	
thin-film		Amorphous silicon (a-Si)
organic		OPV
Construction:		
metal	Aluminium/V2A stainless steel mounting components	Aluminium/V2A stainless steel mounting components
glass		Heat-strengthened safety glass/PV glass
Device:		
metal	Aluminium (PV modules) Steel (balance-of system)	Aluminium (PV modules) Steel (balance-of system) Lithium (battery)
semiconductor	PV cell, inverter	PV cell, inverter, battery charger
plastic		Inverter (case), LED lights (cover)
liquid		Batteries (electrolyte)
Social		
aesthetic		Provides aesthetic value to the building
social impact	Contributes to building energy mix and provides economic value	Contributes to building energy mix and provides economic value

Solar irradiation for each surface: in kWh/m^2 for each of 8760 h a year and average irradiation in kWh/m^2/year at a location selected (e.g., at latitude 32.7° and longitude −117.2°

(San Diego, CA, USA); for BAPV:1939 kWh/m^2/year for global in-plane irradiation; for BIPV: 1214 kWh/m^2/year for southwest wall, 1121 kWh/m^2/year for southeast wall).

SYSTEM COMPONENTS:

PV energy conversion

PV capacity (e.g., for BAPV—25 kW$_{peak}$), for BIPV—30 kW$_{peak}$).

PV material: in BAPV—monocrystalline silicon (c-Si); in BIPV—thin-film (a-Si) and OPV.

PV cell efficiency: in BAPV—22%, in BIPV—6% for a-Si, 11% for OPV.

PV cell structure (e.g., substrate): in BAPV—glass; in BIPV—plastic (a-Si), OPV substrate material—10 µm and 100 µm polyethylene terephthalate (PET).

PV module structure (e.g., front glass, encapsulant, back-sheet, frame, junction box): in BIPV—according to c-Si module specifications; in BIPV—according to a-Si and OPV module manufacturer's specifications.

Maximum power point tracking (MPPT) controller: in BAPV—built into grid tied inverters; in BIPV—MPPT controller may be added for off-grid operations.

Surface application/integration structure: in BAPV—roof and façade mounting; in BIPV—second-skin façade, glazing (transparent/translucent).

Inverter (15 kW)

Inverter materials: according to manufacturer's specifications.

Inverter compliance: in BAPV—to IEEE 1547-2003 standard [63]; in BIPV—to IEEE 1547-2018 standard [64,65].

Battery-based storage (100 kWh, BIPV only)

Battery material: lithium-ion.

Battery structure (e.g., cathode, anode, separator, electrolyte, housing): according to manufacturer's specifications.

Battery charger: according to manufacturer's specifications.

Meter(s)/submeter(s)

Meter materials: according to manufacturer's specifications.

Metering infrastructure: in BAPV—smart bi-directional or dual meters supporting two-way electricity flows; in BIPV—smart unidirectional net meter or dual meters [66].

Balance-of-system

Hardware: wiring, switches, electrical panel/subpanels with breakers and fuses in BAPV/BIPV according to manufacturer's specifications.

Software: asset management system, energy management system, etc., in BAPV/BIPV according to vendor's specifications.

ENERGY LOSSES:

Performance Ratio (also known as Total Derate Factor), %

(e.g., for BAPV—18.3%, for BIPV—7.5%),

Total Loss Factor, %

(e.g., for BAPV—81.7%, for BIPV—92.5%)

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