Supplementary Material

Functionalizing building envelopes for greening and solar energy: Between theory and the practice in Egypt

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Supplementary Tables

Supplementary Table S1: Descriptions and Definitions of greening systems and subsystems that can be implemented on building envelop elements (rooftop, façade, and balcony). Alternative nomenclature for some types was identified from reviewed studies and reports. *BIVs:* Building-Integrated Vegetation systems that plant vegetation, greenery, or decorative plants on building envelopes (e.g., flowers, succulents, foliage plants, etc.), *BIAs:* Building-Integrated Agriculture systems that produce edible plants on building envelopes (e.g., vegetables, fruits, herbs, etc.), *DWC:* Deep Water Culture, *NFT:* Nutrient Film Technique, *LWS:* Living Wall System. This table is complemented by Figure 3 and Figure 4 in the article.

System	Description	Alternative Nomenclature	Reference Code No.
BIVs on Rooftops (Rooftop Greenery systems, vegetated roofs, living roofs)			
Green roof	Rooftop (flat or slopped) covered with green vegetation and growing medium. It has 3 categories: extensive, semi-intensive, and intensive.	Eco-roof, roof garden, and living roof	(1–3)
a. Extensive	A lightweight thin layer of growing medium (around 6–20 cm thick) on a flat or slopped roof. It grows moss, sedums, and grass and requires less maintenance.	Eco-roof, brown roof	(1,2,4,5)
b. Intensive	A heavy deep layer of growing medium (around 20–100 cm thick) on a flat accessible roof. It grows grass to shrubs and trees and requires irrigation and permanent maintenance.	Roof garden, podium roof	(1,2,4,5)
c. Semi-Intensive	A mix of extensive and intensive systems existing on the same roof.	Semi-extensive	(1,4)
BIAs on Rooftops (Rooftop Agriculture systems, Agri-rooftops, rooftop farming systems, rooftop farms)			
Unconditioned system	A low-tech system that is open to the external environment, subject to higher losses of crops, but is less capital and energy intensive. It could host soil-less or soil-based systems.	Open-air rooftop farming	(6–8)
Conditioned system	A high-tech system that uses conditioning/environmental control (active or passive) to allow year-round production. It requires a greenhouse or indoor space on the roof. It could host soil-less (more common) or soil-based systems. It has 2 categories: passive and active. *Passive: lighting and conditioning provided by solar energy. Active: lighting and conditioning provided by conventional fuels or electricity.*	Technological rooftop agriculture, controlled-environment agriculture	(6,8–11)
Rooftop greenhouse	A lightweight construction (a vaulted steel structure enveloped with a polyester screen) that hosts agricultural systems. It could be conditioned or unconditioned (low or high-tech).		(6–8,12)
Soil-based containerized farming system	Containers (low-cost) are laid directly on the waterproofed roof surface. It uses soil or lightweight substrate (peat moss, vermiculite, or perlite).	Informal rooftop agriculture	(3,9,10,12)
a. Rigid containers	Containers of different sizes and materials, waterproofed, and equipped with drainage (e.g. clay pots, wooden boxes, reused vessels, and tires). They could use different growing media.		(3,12)
b. Raised beds	Cultivated beds (tables) that use soil/substrates to accommodate deep-rooted plants (e.g. tomatoes, cucumbers, lettuce, etc.). They can be filled with the substrate or filled with pots.	Cultivation beds	(3,12)
c. Soft planters	Planters such as grow bags/slabs (filled with different growing media), wading pools, and mats (polyurethane foam) are used to accommodate root crops, vegetables, and even fruits.		(3,12,13)
Soil-based organoponics	Containers/raised beds filled with a mix of soil and organic matter or compost. This technique has been commonly used in Venezuela and Cuba.		(11,12,14)
Soil-based green roof agriculture	Green roof system used for edible crop production. The lightweight limited depth of soil is suitable for some plants. It is usually intensive but extensive systems can be used as well.	Formal rooftop agriculture, edible green roof, intensive green roof agriculture	(3,6–10)
Soil-less (water-based) farming System	A system that uses water and nutrients instead of soil for growing vegetables and fruits (e.g. peppers, lettuce, bananas, strawberries). It is differentiated according to the nutrient solution delivery into hydroponics, aquaponics, and aeroponics.	Aquaculture, hydroculture, soil-less culture	(3,9,10,12,15)
a. Hydroponics	A system based on water only, in which roots are dipped in the nutrient solution (directly added to water) without any solid medium.		(3,11,12)
• Deep Water Culture (DWC)	Tanks/buckets filled with water rich in nutrient solution. Plants are grown on polystyrene trays that float on the tank and roots are partially immersed.	Float hydroponics	(12,13,16)
• Nutrient Film Technique (NFT)	Channels (referred to as tubes, gullies, or gutters) filled with a continuous flow of a thin layer of water and nutrient solution where plant roots grow.		(12,13,16)
• Dutch buckets	Drip system of buckets (2.5 gallons) that accommodate plants. The nutrient solution is held at the bottom of the bucket and recycled using a pump.		(16,17)
• Column system	A hydroponic system that uses stacked pots or columns containing lightweight medium to allow the vertical growth of plants.		(12,18)

System	Description	Alternative Nomenclature	Reference Code No.
b. Aeroponics	A System that consists of stacked pots/pockets, where the nutrient solution is provided in the form of high-pressure mist sprayed at plants' roots.		(3,12,13,15,16)
c. Aquaponics	A Hydroponic unit incorporating aquatic species (fish or shellfish) in the tanks, where the nutrient solution is provided by fish wastewater.		(3,11,12,15,19)
Soil-less (sand-based) Sandponics	A system that uses sand as the main growing medium for crops. They can incorporate aquatic species (fish or shellfish) into the system.		(13,20,21)
BIVs on Façades/Balconies (Vertical greenery systems, vertical greening, vertical greens, vertical gardens)			
Green Façade	Façade covered with green vegetation (growing climbing plants such as creepers and ivies). It has 2 categories: direct and indirect.	Climbing façade, green wall adjacent to building, green curtain	(4,5,22,23)
a. Ground-bound (direct)	Climbing plants that are directly connected to the façade (rooted in the ground or grow from garden beds on the ground). The conventional way of greening façades.	Direct façade greening, direct greening system	(1,22)
b. Façade-bound (indirect)	Climbing plants using structural supports with a gap from façade (e.g. trellis, guides, mesh, or planter boxes). Plants grow from containers installed at different levels across the building.	Indirect façade greening, indirect greening system	(1,22)
Living Wall System (LWS)	Modular panels or 'containerized' planters that create a vegetation cover on the façade. It uses hydroponics or other growing media (soil, felt, perlite).	Green wall, living wall, bio-wall, vertical garden, modular LWS	(1,4,5,22,23)
a. Continuous (soil-less)	A lightweight thin layer (small depth) of vegetation cover using a fabric layer or porous screen and a hydroponic system for water and nutrients.		(2,22)
b. Modular (soil-based)	Modules (e.g. Trays, Vessels, Planter tiles, and Flexible bags) filled with soil or lightweight substrate of greater depth to host plants on the façade.		(2,22)
Indoor living wall	A vertical greening system installed on indoor walls for air filtration and enhancement of aesthetic values of the indoor spaces.	Bio-wall, bio-filter, indoor greening	(1,24)
Planter boxes/pots	Low-tech boxes and pots of different sizes and materials with suitable pores for aeration and water flow during irrigation are laid on the balcony floor. It is used to grow decorative plants.	Balcony garden, planter box greening	(25,26)
BIAs on Façades/Balconies (Vertical farming, façade farm, productive façade systems)			
Unconditioned system	A low-tech system implemented on exterior façades and is open to the outdoor environment.	Vertical farming	(27,28)
a. Water-based system on façade	A vertical farm on the exterior façade that uses soil-less techniques, mainly hydroponics (NFT, planters, containers, etc.) to grow productive plants.		(12,29,30)
b. Soil-based system on façade	A vertical farm on the exterior façade that uses soil or lightweight substrate in horizontal planters mounted on the wall to grow productive plants.		(27,28)
Conditioned system	A high-tech system that uses conditioning (environmental control) to allow year-round production in multi-levelled indoor vertical farms.		(11,31)
a. Vertical farm	High-tech vertically "stacked up greenhouses on top of each other" (3) to produce crops indoors (inside buildings). It can grow leafy and rooted vegetables and fruits using water-based systems (hydroponics, aeroponics, and aquaponics).	Vertically integrated greenhouse, vertical farming	(3,11,31–34)
Planter boxes/pots	Low-tech boxes and pots of different sizes and materials with suitable pores for aeration and water flow during irrigation are laid on the balcony floor. It is used to grow productive plants (usually herbs).	Balcony farm, planter box farm	(26)

Supplementary Table S2: Descriptions and Definitions of solar energy systems and subsystems that can be implemented on building envelop elements (rooftop, façade, and balcony). *BAPVs:* Building-Applied Photovoltaic systems are mounted on or externally attached to building envelopes to produce energy from solar resources, *BIPVs:* Building-Integrated Photovoltaic systems are integrated into the building envelopes replacing some of its components, *PVs:* Photovoltaic panels, *PVTs:* Photovoltaic thermal systems, *BAPVTs:* Building-Applied Photovoltaic thermal systems, *BIPVTs:* Building-Integrated Photovoltaic thermal systems, *HVAC:* Heating, Ventilation and Air Conditioning. *ST:* Solar Thermal systems, *SWH:* Solar Water Heaters, *STPV:* Semi-Transparent Photovoltaics. This table is complemented by Figure 7 and Figure 8 in the article.

System	Description	Reference Code No.
Classification by Technology		
Photovoltaic systems (PVs)	A semiconductor device that converts sunlight falling on it into electricity. The term "photo" refers to light and "voltaic" to electricity, also referred to by "solar cell". PV technologies can be applied as Building-Applied or Integrated systems (BAPV/BIPV) and can be classified as conventional and emerging solar cells in nature.	(35–38)
a. Crystalline solar cells	A solar cell made from crystalline silicon as a semiconductor. It is considered the conventional, most common cell in the market. It has 2 categories: single and poly crystalline wafers.	(35,37–39)
• Mono-crystalline	A silicon cell (also referred to as a single crystal cell) produced by slicing single-crystal Si rods into thin wafers. It has higher purity and efficiency (made of a single crystal) but has higher costs. The best cell efficiency is high 22-26%.	(35–40)
• Poly-crystalline	A silicon cell (also referred to as a multi-crystalline cell) produced by melting several fragments of silicon to form wafers. It has lower efficiency (made of several crystals) but has lower costs. The best cell efficiency is 14-18%.	(35–40)
b. Thin Film solar cells	A thin-film solar cell is a more flexible option composed of thin layers of semiconductor materials deposited on a solid supporting material (thickness is in nanometers or micrometers). It is easier to handle, has lower costs and lower efficiency compared to the conventional.	(35–39)
• Amorphous Silicon	A cell made of Amorphous silicon (non-crystalline silicon) and produced by depositing thin silicon layers on a glass substrate. The best cell efficiency is low 6-8%. It is the oldest and most established thin film type.	(35–39)
• Cadmium telluride	A cell made of thin film layers of Cadmium Telluride cells. It is the most common thin film type available with lower production costs compared to other thin film and conventional cells. The best cell efficiency is 9-11%.	(35–39)
c. Emerging solar cells	Third-generation cells that cover several emerging concepts in the solar cells market ranging from the low-cost, low-efficiency to the high-cost, high-efficiency systems that aim at having an overall lower environmental footprint.	(35,37,38,41,42)
• Organic	A lightweight, thin, and flexible cell made of thin films of carbon-based polymer/molecules. It has lower a lifetime and efficiency, but has fewer lifecycle impacts, and lower energy and carbon payback times. The best cell efficiency is 12%,	(35,38,41–43)
• Dye-synthesized solar cell	A semitransparent, thin, and flexible cell that uses molecular dyes in its structure, therefore preferred for building applications. It has high theoretical efficiency, low cost, and easy production. The best cell efficiency is 11%.	(35,38,41–43)
• Pervoskite solar cell	A cell made of a mix of organic–inorganic perovskite material (lead type) in its active layer. It has low production cost, and high efficiency, but has an eco-toxicity impact due to Lead compounds. The best research cell efficiency is 23%.	(35,38,41–43)
Photovoltaic Thermal system (PVT)	A system that produces electrical and thermal energies by combining photovoltaic and solar thermal components in one integrated system. It can be used as PVT solar heating, PVT solar heat pump/air-conditioning, and building integrated and applied systems (BIPVT/ BAPVT). It is classified according to the cooling fluid and collector type into 3 categories.	(36,43,44)
a. Water PVT Flat Collector	A flat collector used for water heating and electricity production. Water used to cool down the PV panel (to improve its efficiency), gets heated and reused inside the buildings as domestic hot water. It has higher efficiency than air collectors.	(36,43,45)
b. Air PVT Flat Collector	A flat collector used for HVAC applications and electricity production. Air used to cool down the PV panel is then used for building heating and cooling. It has lower efficiency than water systems but has low construction/operation costs.	(36,43,45)
c. PVT Concentrator	A PVT collector composed of concentrating parabolic collectors used to maximize the electricity and heat production for the unit area. The concentrating PV has better performance than flat collectors at higher temperatures.	(36,46)
Solar Thermal system (ST)	A system that acts as a heat exchanger transforming solar energy into heat energy (internal energy of the transport medium of the system).	(36,47)
a. Solar Water Heaters (SWHs)	An application of ST systems that changes the received solar radiation into heat transferred to the heating fluid (usually water) to supply the building with hot water. It has reasonable costs and easy application. It has 2 categories: Active and Passive SWHs and has different types of collectors: flat plate, evacuated tubes, and concentrating collectors.	(36,47,48)
• Active SWH	A system that uses a pump to push the heating fluid between the collector and storage tank. It is more expensive, more resource intensive (uses electricity) and has more complex application, but is more efficient. It is more suitable for industrial applications where the tank and collector can be distant apart. It has 2 categories: *Open-loop (direct) system:* Water is heated directly by being circulated between the collector and storage tank. *Close-loop (indirect) system:* A heat transfer fluid (usually an antifreeze) is pushed into the collector and used to heat the service water in the storage tank.	(47,48)

System	Description	Reference Code No.
• Passive SWH	A system that uses heat transfer by natural convection (buoyancy and gravity) where the heating fluid flows naturally between the storage tank (at a higher level) and the collector. It is less expensive and has easy application, but is less efficient. It is more suitable for residential applications where the tank and collector have to be close. It has 2 categories: *Thermosiphon system:* The storage tank and solar collector are separate components with the tank installed at a higher level than the collector. *Integrated collector storage system:* The storage tank and solar collector are one component presenting one compact unit.	(47,48)
Classification by Application		
BAPVs on Rooftops (Building-Attached PVs on rooftops, Building-Added PVs on rooftops, Roof-mounted systems, Rack-mounted PVs)		
Standoff arrays	A system suitable for pitched roofs, PV panels are mounted directly on the roof surface parallel to the pitched roof slope using standoffs (a fixation method). It is more aesthetic, has lower costs, and might produce lower power (roof tilt angle)	(49–52)
Rack-mounted arrays	A system suitable for flat roofs, PV panels are installed on mounting racks on the flat roof surface such that they have optimum tilt angle and orientation. It is subjected to higher structural loads, has higher costs, and usually less aesthetic.	(49–51)
BIPVs on Rooftops (Roof-Integrated PVs)		
Systems for Opaque Roof	A system where PV panels replace conventional opaque roofing material.	(38,39,50,53,54)
a. Standard In-roof system	PV standard module is integrated into the pitched rooftop structure and finishing. It is a well-established competitive technology but has relatively poor aesthetics.	(39,53)
b. Solar tiles and shingles	PV tiles, shingles, and slates are interlaced with the conventional roof finishing tiles. It is more aesthetic, and easy to install but has a high cost relative to the production.	(38,39,53)
c. Flexible laminates	PV laminates and foils are attached to the rooftop surface (usually pasted to the roof finish material). It is flexible, thus suitable for flat or curved surfaces. It is very light, easy to install, and has good aesthetics but low efficiency.	(38,39,53)
Systems for Roof Openings	A system where PV panels replace a glazed rooftop opening (e.g. Skylights, windows in pitched roofs, etc.).	(35,38,39,50,53,54)
a. Semi-transparent roof system	Semi-transparent PV panels are integrated into the roof opening finishing material (e.g. skylight). It has good aesthetics, and allows for sunlight penetration but has high costs.	(35,38,39,52,53)
b. Transparent roof system	Transparent PV panels are integrated into the roof opening (e.g. skylight). It has good aesthetics, and allows for full sunlight penetration but has high costs. The higher the module transparency, the lower the energy efficiency.	(35,38)
BAPVs on Façade/Balconies (Building-Attached PVs on façades, Building-Added PVs on façades, Façade-mounted systems, Rack-mounted PVs)		
Façade/wall-mounted system	PV panels are mounted directly on the building façade or balcony wall using suitable fixation mechanisms. It could be applied at a tilt angle. It is less aesthetic but easy to install to retrofit existing buildings.	(52,54,55)
Parapet/railing-mounted system	PV panels are mounted directly on the balcony opaque parapet (usually a continuation of the below wall) or the balcony railing. It is less aesthetic but easy to install on existing buildings.	(52,55)
Shading device	A system where PV panels are added as shading devices above windows or balconies (using mounting racks). It is a good option as the best inclination angle for shading is the same for maximum radiation exposure and energy generation.	(27–29,54,56)
BIPVs on Façade/Balconies (Façade-Integrated PVs)		
Systems for Opaque Façade/Balcony wall/Parapet	A system where PV panels replace conventional opaque façade, wall, or parapet material.	(35,39,57)
a. Cladding panels	PV panels are integrated into the façade as cladding panels. It has good aesthetics but has high costs. It usually has lower performance because of orientation limitations but is compensated by the large areas of façades.	(39,53,54,57)
b. Shading devices/spandrels/parapets	PV panels are integrated into the building as shading devices above windows or balconies (e.g. sunshades, sunscreens, etc.), or as spandrels and balcony parapets.	(35,39,54,55,57)
c. Trombe wall	A passive solar heating/cooling system that integrates opaque PVs to convert the collected heat from the solar radiation into thermal energy dissipated into the interior space, while simultaneously producing electricity.	(35,52,58),
Systems for Façade Openings/Balcony Railings	A system where PV panels replace a glazed opening material (e.g. window, curtain wall, etc.), replace the balcony transparent or latticed railing, or used as a semi-transparent or transparent shading device above windows and balconies.	(35,38,52,57)
a. Solar glazing	Semi-transparent or transparent PV panels used as glazing panels to allow for unobstructed views and daylight penetration. It combines energy generation, thermal insulation, and daylighting, but has generally low efficiency.	(35,38,57)
Innovative Systems	Advanced systems that are not yet established such as double skin façades, interactive façades, rotating/moving façade skin components, etc. They usually aim at advanced aesthetics and performance but are still expensive.	(35), (57)

Supplementary Table S3: List of References corresponding to the reference code numbers used in supplementary Table S1 and supplementary Table S2.

Reference Code No.	Reference
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Supplementary Table S4: List of References corresponding to the reference code numbers used in Table 1 and Table 2 in the article.

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