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Solar Green Roofs: A Unified Outlook 20 Years On

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Dedicated to Dr. Raffaella Galiano, chemist and entrepreneur, for all she did to advance clean technology in Italy in the course of the last decade

Solar green roofs, namely, rooftops functionalized with properly selected living vegetation and photovoltaic modules, achieve an ideal symbiotic relationship in which the promotion of biodiversity and onsite renewable energy production are enhanced, while the roof provides a range of environmental, health, aesthetic, and economic benefits. This study provides a unified outlook of this important sustainability technology before its large-scale uptake across the world, especially in polluted urban areas.

1. Introduction

In early 2017, less than 5% of buildings globally were functionalized with photovoltaic (PV) modules.[1] Hence, we recently provided arguments and recommendations to undertake a global effort using today's largely affordable solar PV technology to functionalize the existing building stock.[2]

For decades impeded by the high cost and by the poor aesthetics of PV technology, this shift is now technically and economically viable, thanks to the truly global "solar boom"[3] that occurred in the last decade that led to the dramatic progress in the PV industry.

Almost concomitantly, the green roof technology evolved from the roof-garden concept to the extensive green roof, comprising a light system of layers having a thin soil depth and drought-resistant vegetation on top.[4]

In general, green roofs add a wide range of environmental, health, economic, and aesthetic benefits such as reduced energy consumption for heating, habitat restoration, and increased urban biodiversity, rainwater retention, reduced noise and air pollution, and mitigation of heat island effect.[5]

Only in terms of real carbon sequestration potential, data from the two studies on vegetated roofs to quantify the carbon accumulation potential of green roofs (in both plant biomass and soil substrate) point to 187.5 $\text{g C m}^{-2}\,\text{year}^{-1}$ of carbon removal rate, which is equivalent if all Detroit's roofs were covered with such a roof to sequester almost 28 000 tonnes of carbon every year from air.[6]

Aptly called "biosolar roofs"[7] to underline the symbiotic role in promoting biodiversity and onsite renewable energy production in the urban built environment, green solar roofs are rooftops functionalized with PV modules and properly selected vegetation.

In comparison with the conventional green roofs, biodiversity is enhanced because the PV modules on the green roof provide on their back an excellent microhabitat for insects and birds, whereas the shadow behind the panels results in better and more diverse living and vegetation conditions due to the substrate retaining moisture.[8]

Production of electricity increases (see in the following) because the green roof lowers the roof's temperature compared with conventional roofs.[9]

Despite all these benefits, the number of solar green roofs across the world reported in late 2018 was "rather rare,"[10] and was found "nearly nonexistent" in 2016.[11]

Three years later, the price of PV modules has broken the \$0.30 W^{-1} threshold with average module prices priced \$0.278 per watt for standard polycrystalline silicon modules by mid-2018 (\$0.337 per watt for polycrystalline passivation layers technology [PERC] modules and \$0.363 per watt for monocrystalline PERC modules).[12]

Similarly, the efficiency and durability of PV modules, with the widespread adoption of the rear PERC,[13] have reached such high levels to make the adoption of PV energy on all world's building within the next two decades, providing a reasonable forecast and expectation.

This study offers a unified outlook of the important solar green roof technology focusing on practical aspects that so far have prevented its widespread uptake across the world, especially in polluted urban areas.

Its outcomes will hopefully aid to expand and improve the knowledge of green solar roofs, which is often poor even among rooftop solar energy practitioners and energy managers.

2. Technology and Ecological Aspects

Especially well suited for large flat roofs in urban areas, today's extensive green roof technology uses a multilayer system, with a

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waterproof membrane at the bottom, a drainage layer, a soil growth substrate (with a filter layer separating it from the drainage layer), and the vegetation layer comprising plant species able to withstand drought conditions and to survive under minimal nutrient conditions.[14]

The water content of a green roof, with its wet soil and drainage layer, is always significant, making mandatory the insertion of a root-resistant waterproof membrane for any quality (long-lasting and defect-free) solar green roof. “A single drop of water leakage in roof,” written by Vijayaraghavan, “should be considered as a failure of green roof.”[14]

Compared with a conventional extensive green roof, a solar green roof includes an extra layer (“solar base”) to lay the frames on which the PV modules are eventually installed. The whole installation is straightforward and takes place in six steps.[9] Using aptly developed PV module-mounting frames, there is no need for roof penetration because the green roof provides the superimposed load required to protect the system against wind uplift (**Figure 1**).[9]

Although *Sedum* species were the dominant plant chosen for extensive green roofs for over two decades, succulent plants have lately emerged as suitable plants especially in hot climates because these species can withstand longer periods of drought and are more likely to resume growth soon after water is made available.[15]

Testing a properly installed set of PV modules over a green roof comprising eight plant species including *Opuntia fragilis* (**Figure 2**), a team of scholars in Colorado found that the shade cast by the PV module string during the morning hours establishes gradients in substrate moisture, solar irradiance, and temperatures, with the substrate surface acting as a thermal sink relative to exposed roof surfaces.[16] The temperature variations below the PV modules, for example, were markedly lower amounting to 3.92 and 6.36 °C, for the substrate surface beneath the modules in sheltered areas and in exposed areas, respectively.

The green roof areas beneath and close to the PV array remained fully vegetated, whereas coverage in the exposed areas was patchy which is, the scholars noted, a typical condition in moisture-deprived plants exposed to high levels of direct solar irradiance (bottom of Figure 2).[16]

Figure 1. The green roof provides a superimposed load. There is no roof penetration, thanks to the superimposed load principle (photograph courtesy of ZinCo GmbH).

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As mentioned earlier, the biodiversity potential habitat for wildlife in a solar green roof is enhanced in comparison with a green roof and can be further enhanced using competences from horticulturalists and conservation scholars.[4,8]

For instance, since 1999, the green roof on the Hall 1 of Messehalle Basel (top of **Figure 3**, in Switzerland) with its 7 cm of volcanic substrate planted with low-growing *Sedum* species, flowering herbs, and forbs includes a large PV array deployed over 1900 m^2 of the green roof that produces 215 000 kWh year^{-1}.[17]

In 2008, Brenneisen, a conservation scholar, added organic matter and woody debris to the roof, thereby enhancing its biodiversity functions (Figure 3).[17]

The biosolar roof system in the subsequent years worked so well that in late 2013, a new PV array comprising 4517 PV modules in monocrystalline silicon for an overall 1189.1 kW peak power was installed with east–west orientation on the green roof of the new Messe Basel hall complex.[18] The plant is due to produce around 1 080 000 kWh of clean electricity each year.

Another option, in addition to conventional south-facing or east–west orientation of tilt PV modules, is to mount the modules vertically, especially when using new-generation bifacial modules (i.e., modules with solar cells on both module sides).

This was again demonstrated by scholars in Switzerland installing a 9.09 kW PV array of custom-made bifacial PV modules with 20 solar cells (to reduce the wind load and to improve

Figure 2. Effects of protection from the PV array on the green roof (top) where vegetation appears to have greater coverage (bottom left) in areas shaded from direct sunlight for a portion of each day (bottom right). Reproduced with permission.[16] Copyright 2017, Green Infrastructure Foundation.

Figure 3. The solar green roof completed in 1999 on the Hall 1 of Messehalle Basel (after addition of organic matter and woody debris in 2008). (Photograph of Jim Labbe, reproduced with permission.[17])

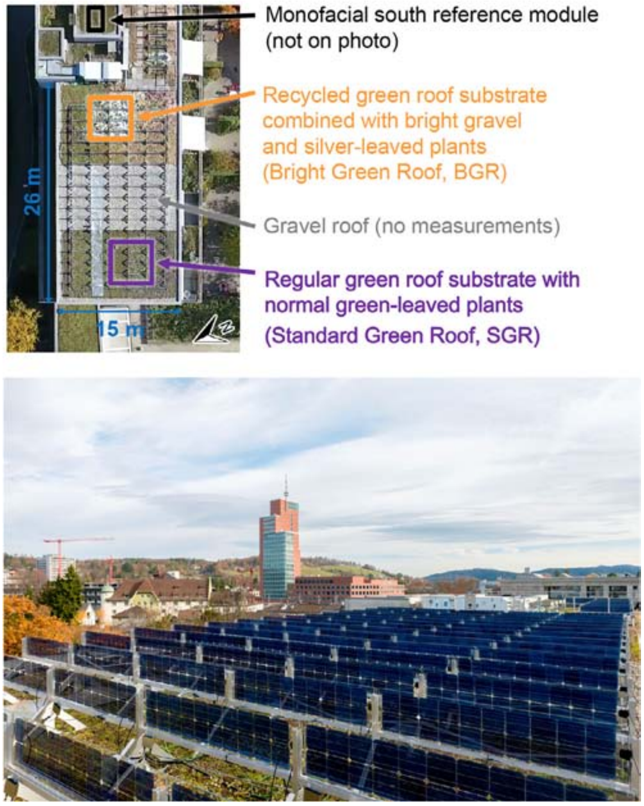

Figure 4. Aerial (top) and later (bottom) view of the 909 kW PV array on the rooftop of a building of Zurich University of Applied Sciences in Winterthur (photograph courtesy of T. Baumann and Zurich University of Applied Sciences).

the general appearance) on the rooftop of a building of Zurich University of Applied Sciences in Winterthur.[11]

The rooftop was partitioned into three parts: a regular green roof substrate with normal green-leaved plants, a gravel roof, and a recycled green roof substrate combined with white gravel and silver-leaved plants (**Figure 4**, top).

In 1 year of continuous monitoring (between August 11, 2017, and August 10, 2018), the PV array over the bright green roof comprising the bright substrate and silver-leaved plants achieved a specific yield of 942 kWh kWp^{-1}, almost identical (−1.4%) compared with that measured for a south-facing monofacial PV module (25° azimuth and 16° tilt) affording 1000 kWh kWp^{-1}.[11]

The use of plants with good reflective properties, which are also well suited to the ambient conditions on flat roofs, resulted in a clean electricity yield increase of 17% compared with a standard green roof planting having a measured albedo (0.09) less than half of the albedo measured for the bright green roof (0.21).

Solar green roofs retain most of the benefits of conventional green roofs, including enhanced thermal insulation, the ability to lower urban air temperatures, and mitigate the urban heat island effect (reducing the ambient air temperature by 4.2 °C in Singapore's tropical climate),[19] while providing a more aesthetically pleasing urban or extra-urban landscape.

As expected, compared with conventional green roofs, the green roofs with integrated PV modules are less effective in reducing stormwater runoff and peak flow. This has been lately demonstrated by scholars in Canada who reported that during small and medium rainfalls, a portion of rainwater is intercepted by the PV panel surface and concentrated into a narrow strip of the green roof along the panel dripline.[20]

In detail, while in the case of large rainfalls, the difference between the conventional green roof and the solar green roof in terms of rainwater retention was minimal, the solar green roofs produced discharge with rainfalls in excess of 3 mm (**Figure 5**),

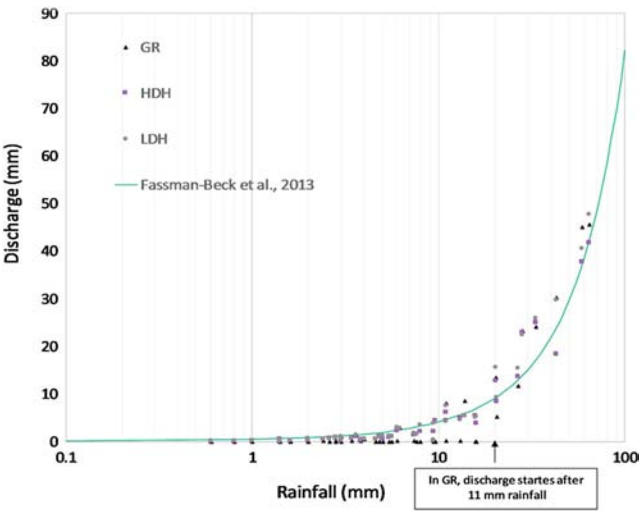

Figure 5. Discharge versus rainfall for solar high differential height (HDH), low differential height (LDH) and conventional green roofs (GRs). Reproduced with permission.[20] Copyright 2018, Elsevier.

whereas in the conventional green roof, discharge rarely occurred from events with less than 11 mm of rainfall.[20]

In principle, the combination of green roofs with PV modules should result in the higher production of clean electricity due to the cooling effect of the vegetation especially during summer's hottest days when the surface temperature of a green roof rarely exceeds 30–35 °C.

Scholars based in Israel, however, recently reported no differences in electricity production after testing for 2 years adjacent PV modules installed on concrete with a bitumen membrane and on a green roof (**Figure 6**).[21]

The finding was due to the lack of significant differences on the average temperatures measured behind the module which in turn was due to the strong winds common in the area which effectively cooled the module on conventional roof, as well as to limited evapotranspiration from vegetation in summer months featuring poor or no rainfall.

Similar findings were reported by scholars in Singapore after comparing the temperature for a PV module on green and concrete roofs.[22] Again, no difference was observed between the average of maximum daily temperature of a PV panel in each season in conventional and green roofs due to high wind speed throughout the year and poor rainfall in warm months, with wind that under the PV module on the green roof was obstructed thereby reducing its cooling effect.

Figure 6. The PV modules on conventional and on green roof tested in 2016 and in 2017 at the University of Haifa (photograph courtesy of Professor Bracha Schindler).

Indeed, the outcomes of similar measurements carried out in a less windy region of Germany using adjacent PV modules placed on a conventional bitumen waterproofing membrane and onto a green roof (**Figure 7**) clearly showed a difference in the values of the average daily temperature beneath the modules amounting to about 8 °C throughout the year.[9]

Subsequent measurements lasting since over 3 years invariably point to the same significant difference.

Numerous other studies have shown a positive cooling effect of green roofs on the temperature of PV modules and thus on energy production. Suffice it to cite here a year-long experimental study comparing the energy output of a 4.23 kWp PV array installed over the roof of an educational building at the University of Kansas.[23]

In detail, nine PV modules in polycrystalline silicon were placed over a *Sedum* green roof (*Sedum* needing minimal

Figure 7. The PV modules tested during one solar year installed on bituminous membrane and on a green roof (photograph courtesy of ZinCo GmbH).

Table 1. Monthly energy and difference for the PV arrays installed over the green (EP-green) and bitumen membrane (EP-black) roof at the University of Kansas' Center for Design Research. Reproduced with permission.[23]

Month	E_{green} [kWh]	E_{black} [kWh]	Difference [kWh]	Difference [%]
January	48.18	47.67	0.51	1.1
February	102.86	102.47	0.39	0.4
March	84.36	83.93	0.42	0.5
April	141.82	141.86	−0.04	0.0
May	141.59	139.77	1.82	1.3
June	254.52	239.79	5.73	2.4
July	198.87	194.87	3.99	2.0
August	165.85	163.13	2.72	1.7
September	131.14	130.53	0.61	0.5
October	94.28	92.86	1.41	1.5
November	48.56	47.65	0.91	1.9
December	36.32	35.36	0.96	2.7
Total	1439.34	1419.90	19.43	1.4

amount of solar radiation and irrigation) and nine over a bituminous membrane. All modules were facing south with a 10° tilt angle. Each module had a temperature coefficient of the power of $-0.0045\ \mathrm{W\,^{\circ}C^{-1}}$. The energy production from the two PV arrays was measured during a complete solar year (**Table 1**).

The energy production of each individual solar module was measured via microinverters installed under each PV panel and the underside module surface, whereas the ambient air temperature was measured with sensors that also returned the relative humidity.

After 1 solar year, the energy production of the solar green roof for the entire year was 1.4% higher than that for the PV system over the conventional rooftop.

The difference in energy production between the two arrays was higher during the hottest days of the year, namely during June and July when the greatest variations in energy productions were recorded and when the energy production of PV systems achieved its highest levels.[23]

On average, the hourly underside surface temperature of the PV modules on the bituminous membrane was about 3 °C higher than that measured on the green roof, while the maximum difference was ≈6 °C.

The highest differences were recorded during the peak temperature of the day, suggesting that such differences will be even higher in warmer regions of the world, with more days of ambient air temperatures above 25 °C, such as in many African and Indian regions as well as in Middle East countries, and in urban areas where average temperatures are higher than in extra-urban areas.

3. Solar Cities, Urban Habitats

The solar city concept, namely the use of the urban built environment to generate electricity via building-integration of PV modules, is not an utopian "scenario" for environmentalists but a realistic option whose relevance derives from a finding that more than 60% of a typical city daylight electricity need and over 30% of its all-hours demand can originate from such distributed energy-generation approach.[24]

Referring to Rome and to the need to preserve the architectural integrity and historic value of the built environment, we have lately identified the technology solutions and the policy and educational initiatives to effectively achieve such global uptake of decentralized solar energy systems within the next decade (2018–2027).[1]

Green solar roofs are particularly necessary in large cities to combat air pollution and for restoring biodiversity in urban areas.

In general, the fuel combustion in the internal combustion engine (ICE) of hundreds of thousands or even million vehicles systematically pollutes the air of cities across the world, threatening the health and well-being of people living or visiting highly polluted cities.[25]

As lately shown by the city of Shenzhen, replacing the whole diesel bus and nearly all (95%) of its taxi fleets with 16 359 battery electric buses and more than 19 000 battery electric taxis, air pollution from ICE vehicles will be ultimately resolved by electric vehicles.[26]

The contribution from green solar roofs to this evolution toward sustainable cities includes the concomitant generation of clean electricity and oxygen-rich, clean air, where it is most needed while restoring biodiversity.

As put it by Brenneisen in 2006, when green roofs were still limited exclusive to a few examples:

> As a potential tool for preserving and restoring biodiversity in urban areas, green roofs need to be seen less from the perspective of ornamental gardening and energy conservation and more from a regional perspective of landscape and ecological planning.[27]

Large flat rooftops plentiful in cities are ideally suited for the installation of solar green roofs as they allow to minimize the cost of installation, enhance electricity generation, contribute to clean the air, thanks to new vegetation, and promote biodiversity.

In addition to the aforementioned Basel's Messe examples, these outcomes are clearly shown by London's 2500 m^2 green solar roof installed on the rooftop of a new building completed in July 2011 (**Figure 8**), on the occasion of the 2012 Olympic Games.

The conclusions of a subsequent study monitoring the biodiversity of the extensive green roof were clear:[8] 92 plant species recorded on the roof, with the PV modules acting as refugia for plants during periods of drought; higher proportion of faunistically interesting invertebrate species in comparison with other green roofs in the same city; regular sightings of black redstart and linnet birds, showing how the green solar roof acts also as a valuable foraging resource for rare (and protected) and common bird species.

4. Outlook and Conclusions

The solar green roof technology is an advanced form to generate clean electricity and provide numerous ecological services in the

Figure 8. The four-storey London Olympics International Broadcast Centre hosts a 2500 m^2 green solar roof whose habitat attempts to mimic the open habitat of the Thames river corridor (photographs from Google Earth).

newly distributed generation energy framework that offers tangible and prolonged benefits in both developed and developing countries.

Both residential and nonresidential buildings are perfectly suited to host green solar roofs, creating at the same time a significant number of new jobs, as a rooftop PV installations support almost three times as many jobs than ground-mounted installations (only in the 28 countries of the European Union, rooftop solar could provide 150 000 jobs by 2021).[28]

In India after the government announced the Jawaharlal Nehru National Solar Mission in 2010, rooftop installations went from 0 to 2538 MW as of March 2018, growing annually at a compound annual rate of 117% between 2013 and 2014 and 2017 and 2018.[29]

The world's second most populous country targets to install 40 000 MW of rooftop solar power capacity by 2022, and even if only 3 GW had been installed till mid-2018,[29] the opportunities for solar green roofs are truly significant, especially in the country's largest cities where air pollution is a serious public health issue.

Numerous other countries have similar ambitious targets. Turkey, as another example, targets 10 000 MW of rooftop PV (4 000 MW for residential rooftop PV applications and 6 000 MW for industrial and commercial systems) by 2026.

Driven by the low price and ever-increasing abundance of PV modules (global production capacity due to reach 124 GW in 2019 compared with 104 GW in 2017),[30] the global rooftop solar market is expected to achieve compound annual growth rate of above 9% until 2022.[31]

As mentioned earlier, practical progress concerning green roofs has been so rapid that large cities such as Toronto have already devised guidelines[32] aimed at designing true pollinator habitats on green roofs. The concept of the careful planning of green roofs with diverse vegetation as an essential requirement to increase their value as habitats is now widely shared among green roof practitioners.[33]

What remain lesser known are the main energy and ecological implications of solar green roofs among renewable energy practitioners and energy managers, as traditionally the construction of a solar PV rooftop array has not required specialist ecological expertise.

Indeed scholars in Switzerland lately ascribed the poor uptake of the solar green roofs to the lack of proper education in solar energy and in green roof technology, with several cases in which the selected vegetation was wrong, and positioning and orientation of the PV modules were not correct.[7]

New educational, research, and communication efforts will be instrumental in turning a significant fraction of the new solar rooftops into solar green roofs.

Expanding the knowledge and skills of energy managers and practitioners of solar energy with green solar roof science and technology will ideally take place at new solar energy research and educational institutes whose foundation is critically important to shape the professionals needed to guide the transition to renewable energy and to the bioeconomy.[34]

Starting from the energy aspects of green roofs,[35] newly shaped energy professionals will learn how to effectively manage the installation of green solar roofs able to yield large amounts of clean electricity while taking into consideration how each new green roof fits into the broader goal of biodiversity conservation by assessing the potential ecological costs.[36]

As in the case of today's effective courses on solar energy for energy managers,[37] we recommend proper balance between theory and hands-on, practical education, with at least one visit to a well-designed green solar roof, and a minimum of two lectures offered by practitioners of the green roof industry.

Dealing with advanced education aimed at energy managers, the economic and practical aspects of utilizing solar green roofs will be given priority, consistent with the managerial role of today's energy managers.[38]

For example, we remind that when electricity is generated on the roof and consumed in the building, the distributed generation situation is achieved and average losses of 7%–10% from transmission and distribution lines are avoided. Such losses increase exponentially as power lines become heavily loaded so that reducing electricity demand in the highest peak hours can reduce line losses by as much as 20%.[39]

Driven by the urgency of oil, population, and wealth, conflicting dynamics first identified by a single model in 2016,[40] China is facing the otherwise uneasy economic and geopolitical consequences of reliance on imported fossil fuels by deploying a huge amount of renewable power generators fed by water, wind, and sunlight.

In brief, total power generation in China has risen from around 1400 TWh in the late 1990s to 6400 TWh in 2017, when power generation from renewable energy sources reached 1600 TWh moderating the growing fossil fuel gap by 20% (from putative 9600 to 8000 TWh in 2017).[41]

Four root causes were lately identified by Chinese scholars to limit green roof penetration in China's cities: increased maintenance, design and construction costs, poor arrangement of the use of green roofs, and lack of incentives toward developers.[42] The team recommended the deployment of financial incentives and new mandatory regulation together with better dissemination of the benefits "particularly lifecycle cost benefit, among building stakeholders."[42]

No better dissemination argument, we add in conclusion, than focusing on the prolonged economic benefits offered by a solar green roof whose enhanced electricity production will rapidly repay the extra cost incurred to install and maintain the green roof, especially today when the state–of-the-art PV modules are certified to last at least 30 years while losing less than 0.4% of their original productivity every year.[43]

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Conflict of Interest

The authors declare no conflict of interest.

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