12th International Conference
ENVIRONMENTAL ENGINEERING
April 27–28, 2023, Vilnius, LITHUANIA

eISSN 2029-7092
eISBN 978-609-476-342-7
Article Number: enviro.2023.878
https://doi.org/10.3846/enviro.2023.878

A REVIEW ON THE SUSTAINABILITY OF SMART BUILDINGS THAT COMBINE GREEN AND PHOTOVOLTAIC ROOFTOPS IN COLD CLIMATE REGIONS

Dalia Mohammed Talat Ebrahim ALI*

Kaunas University of Technology, K. Donelaičio g. 73, 44249 Kaunas, Lithuania

Received 16 January 2023; accepted 20 February 2023

Abstract. A rooftop of a building could be ultimately utilized to retrofit the implementation of smart and sustainable solutions. Green roof systems play a significant role in terms of reducing heat loss and energy consumption, making them a sustainable solution for countries with cold climates. Additionally, rooftops are a convenient space to install photovoltaic (PV) panels to produce solar energy. According to one German study, the energy produced from solar panels is 7% higher when panels are placed on a green substrate in comparison to when they are placed on hard standings. The combination of both PV and green rooftops in countries with cold climates requires a particular selection of plants and roof design solutions. There are far more studies that cover PV-green roofs in countries with warm or moderate climates. However, not as many for countries with cold climates. This paper sheds light on this area of study to assess the practicability of the integration of PV-green rooftops in cold regions, by reviewing case studies of the benefits and analysis of rooftops utilized by combining PV and green roofs, integrating both solutions to the building's smart energy system, and reusing grey water to maintain the greenery of the rooftop, to attain a sustainable system. The experimental case studies presented in this paper, which are done by different researchers, show that PV-Green rooftops are an advantageous hybrid solution to implement even in countries with harsh winter conditions, and are more sustainable than stand-alone PV panels.

Keywords: photovoltaic panels, green roofs, sustainable, smart buildings, energy.

Introduction

The leading reasons behind the augmented demand to have sustainable energy solutions are the spike in energy costs, the urgency to widely use renewable and clean energy resources, lessen the use of scarce energy, as well as to minimize the consumption of natural resources such as water (Hoyer, 2022). The European (EU) green deal which was approved in 2020 by the European Commission, has initiated policies concentrating on reducing greenhouse gas emissions in Europe by 55% by 2030 and becoming climate neutral by 2050 (Simon, 2019; Tamma et al., 2019). Some of the strategies set by the EU Commission to attain this target are, to transition to renewable energy resources, and to enhance the energy performance of the buildings (Hoyer, 2022; European Commission, 2019). This has led to a growth in the number of smart buildings. A rooftop of a building, even in cold regions, is a space that could be ultimately utilized to design or retrofit the implementation of smart and sustainable solutions to help cool, heat, produce, and consume energy efficiently in the building. Rooftops are mostly utilized by installing either PV panels to produce solar energy, or by implementing green rooftops to promote urban greenery. However, the integration of both technologies is environmentally beneficial in the enhancement of the PV panels and plantation on the roof (Bousselot et al., 2017; Hui & Chan, 2011). Furthermore, greywater could be used to irrigate the plants and it could also be filtered for reuse by the green layer on the roof.

1. PV efficiency in a cold climate

There may be some uncertainties concerning the practicability of adapting households to optimize solar energy in countries with cold climates. This could be the reason behind not having as many studies, observing PV panels efficiency conducted in cold regions as there are in warmer or tropical regions. Experimental studies done by researchers in Serbia (Pantic et al., 2016), and by Zirnhelt and Richman (2015) in Canada, prove that solar energy is a feasible source of energy that could cover a building's energy needs and is of value even when executed

* Corresponding author. E-mail: *dalia_103@hotmail.com*

under harsh winter conditions. A simulation study done by Hachem-Vermette, Cubi and Bergerson (2016) with a scale of approximately 1000 households and facilities in Calgary, Canada, stated that PV panels are an effective part of energy production (Hachem-Vermette et al., 2016). According to a review done by Dubey et al. (2013), PV panels are sensitive to temperature and their efficiency linearly drops as the temperature rises (Dubey et al., 2013). Solar PV cells are more efficient at lower temperatures, which makes temperature-sensitive PV panels convenient to implement in cold climate regions (Pantic, 2016; Dubey et al., 2013; Mansouri Kouhestani et al., 2018; Sheps et al., 2021; Drücke et al., 2021; Mussard, 2017). The experiment conducted in Serbia (Pantic et al., 2016), also verifies that PV efficiency is higher in winter than it is in summer. Figure 1 shows improved efficiency in December (winter) compared to July (summer) (Pantic et al., 2016; Mussard, 2017).

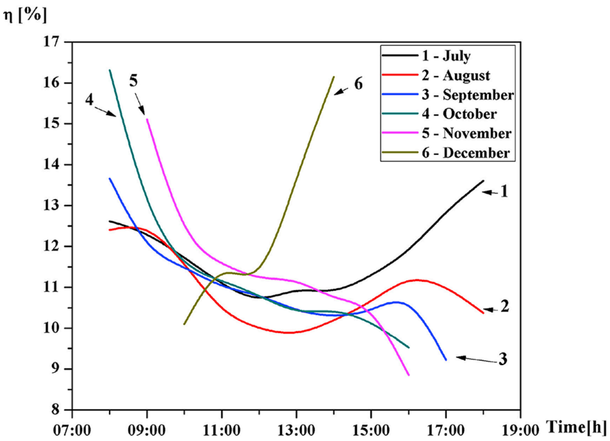

Figure 1. Daily variation of the efficiency (η) of the PV module for various months (Pantic et al., 2016)

2. Green rooftops in a cold climate

2.1. Benefits

There are plenty of benefits that come with the implementation of green rooftops in buildings. Green rooftops are aesthetically appealing and play a significant role in air quality, stormwater management, and heat reduction, and decrease the energy used for cooling and heating (Cubi et al., 2015). Another reason why a green rooftop is a great way to enhance the overall environment and urban surroundings; is that it doesn't take space from roads or streets (Cubi et al., 2015; Schade et al., 2021; Ascione et al., 2013). Studies conducted by Getter (Schade et al., 2021) in a Midwestern U.S. climate, compare hot summers to snowy winters of a green roof and a bare roof. The results showed that the green roof's effect on the heat flux through the roof was larger in summer with a heat flux reduction of 167%, while the reduction in winter averaged only 13%. Moreover, the bare roof was up to 20 °C warmer than the green roof in summer. However, green and bare roofs showed comparable temperatures during winter when it snowed (Schade et al., 2021). Cubi et al. (2015) evaluated the life-cycle performance of green roofs installed in various cold Canadian climate zones and found that they reduced both the heating and cooling energy consumption of the buildings (Cubi et al., 2015).

2.2. Green roof layers and plant selection

A basic green roof system, shown in Figure 2, consists of the following layers: a vegetation layer, growing medium, filter fabric, drainage materials, insulation, and membranes to protect buildings from leaks and prevent plant roots from penetrating the roof membrane (Mahmoudi et al., 2021; Evans, 2015; Kamarulzaman et al., 2014; Vijayaraghavan, 2016).

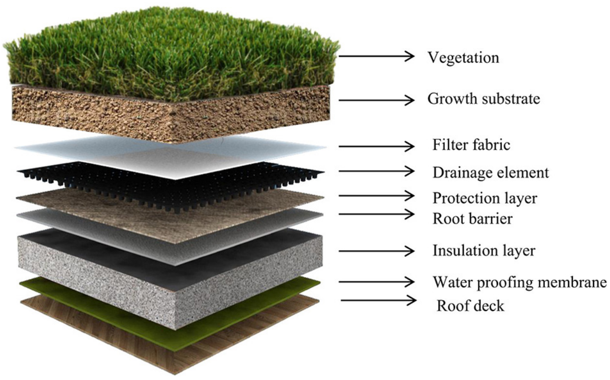

Figure 2. Green roof layers (Vijayaraghavan, 2016)

Selecting the species of plants for plantation on the roof is of high importance (Lönnqvist et al., 2021). The plants selected in cold regions should be able to withstand local temperatures, winds, snow, and rainfall (Pradhan et al., 2019). The cold climatic conditions dictate the kind of plantation that would be suitable to have on rooftops. Moist vegetation based on species from the Crassulaceae family and a lot of Sedum species are used for green roofs in Northern Europe (Johannessen et al., 2017; Xing et al., 2019). A study held in three different locations in northern Sweden in Kiruna, Luleå, and Umeå, which have a cold climate according to the Köppen Geiger climate classification, examines the plantation on 41 sections of roofs on 11 buildings across those locations during the summer and autumn of 2016 and the summer of 2017 (Johannessen et al., 2017). Table 1 presents climatic data of the three locations surveyed from the Swedish meteorological and hydrological institute's database between 1961 and 1990. It could be observed from Table 2 that the total roof coverage of a plant in all surveyed rooftops, differs from one species to another. Hence, plant species influence green roof coverage and vitality (Lönnqvist et al., 2021).

Table 1. Locations and climatic data (for the reference period 1961–1990) taken from the Swedish meteorological and hydrological institute's database (Lönnqvist et al., 2021)

Location	Kiruna	Luleå	Umeå
Lat, Long	67.85, 20.32	65.58, 22.16	63.80, 20.29
Mean temp. °C (max, min daily mean)	−1.9 (24.9–37.9)	1.6 (23.7, −31.1)	2.7 (23.1, −26.0)
Annual snow precipitation, millimeter (%)	500 (40)	506 (35)	591 (35)
Annual precipitation, days	180	162	137

Table 2. The 10 most abundant vascular plant species (by coverage) found on roofs (Lönnqvist et al., 2021)

Species	Mean total cover (min, max)	Standard deviation	Coefficient of variation	No. roof sections where present (%)
Sedum acre	58.1 (0.0, 100.0)	36.4	0.6	38(93)
Poa alpine	6.6 (0.0, 60.5)	16.1	2.4	11(27)
Sedum album	3.0 (0.0, 36.0)	6.1	2.0	27(66)
Festuca ovina	2.2 (0.0, 23.7)	5.1	2.3	19(46)
Epilobium ciliatum	1.6 (0.0, 64.6)	10.1	6.3	5(12)
Poa glauca	1.5 (0.0, 54.0)	8.5	5.7	2(5)
Poa pratensis	0.4 (0.0, 8.8)	1.6	3.9	3(7)
Sonchus arvensis	0.3 (0.0, 11.0)	1.7	4.2	4(10)
Geranium columbinum	0.3 (0.0, 11.3)	1.8	6.4	1(2)
Poa compressa	0.2 (0.0, 10.0)	1.6	6.4	1(2)

3. Integration PV-Green roof

3.1. Benefits of PV-Green roof integration

Combining both a green roof and PV systems on a rooftop promotes a sustainable green building, and improves their effectiveness. The panels work as a shade for the plants and protect them from radiation and extreme sun exposure. This contributes to the enhancement of plant growth, richness, and variety. On the other hand, plants protect PV panels from cold weather conditions because of their thermal capacity (Hui & Chan, 2011; Feng et al., 2015; Lamnatou & Chemisana, 2015). A certain case study done by Kohler in 2007, demonstrated the increase and higher efficiency performance of 6% with PV arrays installed on green roofs (Bousselot et al., 2017). Another study done by Hui and Chan (2011) realized that 8.3% more electricity was generated from PV arrays integrated with green roofs than from stand-alone PVs (Bousselot et al., 2017). To examine the effects of PV-green roof integration, a hypothetical case study has been performed by Hui and Chan (2011) using the software "EnergyPlus" to run four simulation models to calculate the annual energy consumption of an existing building in Hong Kong. The four models were set up to compare findings of the year-round energy performance of a bare roof, a green roof, a PV roof, and a PV-green roof (Hui & Chan, 2011).

The roof models in Figure 3 are in a 12-story office building with a total floor area of 46,320 m^2. In this model simulation experiment, it is assumed that the PV systems of PV roof and PV-green roof have an efficiency of 12% and 13%, respectively, and that the PV system covers a roof area of 2,494 m^2 (Hui & Chan, 2011). The leaf area index (LAI) of the green roof is assumed to be 3 for a typical extensive green roof, whereas the LAI of the PV-green roof is divided into two parts: LAI = 3 for 30% of roof area (exposed) and LAI = 3.5 for 70% of roof area (Hui & Chan, 2011). The comparison of the annual energy consumption of lighting and space conditioning of the four models in Figure 4, demonstrates that PV panels of PV-green integrated rooftops, generate 118 GJ more energy than PV panels on a bare roof. However, there is no significant difference between the bare and the green roof, due to the small green roof area compared to the total building floor area (Hui & Chan, 2011).

An experiment was conducted by Zheng and Weng (2020) in Los Angeles, California, USA for selected buildings at two study sites; Glendale and Koreatown, to study the impact of PV-green rooftop integration. The assessment was done by comparing building demands under the current 1991–2005 and future 2050 under the

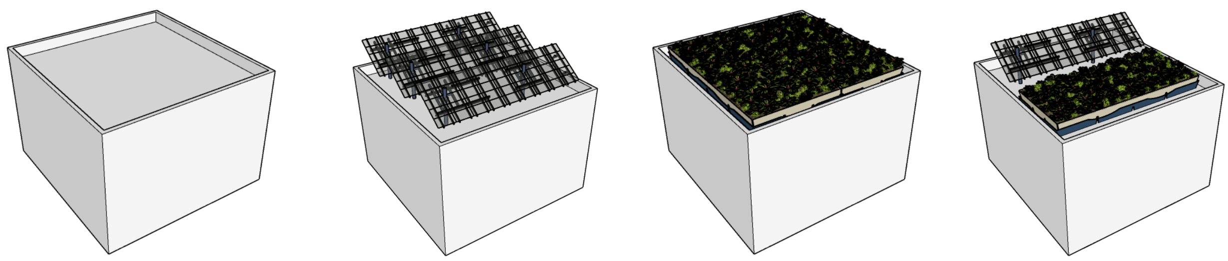

Figure 3. Four different roof models

Intergovernmental Panel on Climate Change [IPCC] A1F1 emission scenario. The results of the experiment show the potential saved electricity when combining both PV and green rooftops in comparison to a standard roof as shown in Figure 5 (Zheng & Weng, 2020).

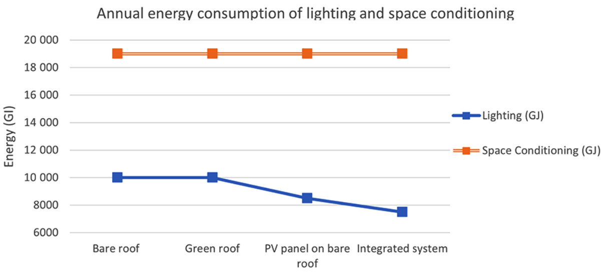

Figure 4. Annual energy consumption of lighting and space conditioning (Hui & Chan, 2011)

3.2 PV-Green rooftop arrangement design

The magnitude of the effectiveness of a PV green rooftop relies highly on the arrangement of a particular building site and the placement of PV panels and plants (Hui & Chan, 2011; Sailor et al., 2011). Figure 6 illustrates possible combinations of PV panels and green rooftops (Zluwa & Pitha, 2021). There are standards and aspects to consider when implementing a hybrid PV-green rooftop arrangement design, such as; PV type and mounting, load on the roof, secured water supply, height and material of the vegetated layer, selected plants, and maintenance effort, to obtain a highly efficient system (Zluwa & Pitha, 2021; Tian et al., 2017).

4. Re-usage of greywater to irrigate green roofs

Greywater generally refers to the wastewater that comes from showers, sinks, and washing machines in households. As stated by some studies, the term "greywater" includes all the wastewater produced at home except for toilet water waste (Mahmoudi et al., 2021; De Gisi et al., 2015). According to international statistics, 2.7 billion people worldwide will face water shortages by 2025 (Mahmoudi et al., 2021). Therefore, the reuse of greywater, particularly for non-drinking purposes, has gained attraction for being an effective strategy to reduce the consumption of purified water in urban areas (Mahmoudi et al., 2021). It can achieve from 10% to 50% potential savings on water use in the household (Pradhan et al., 2019). One of the main reasons behind the restrains of green roofs and green walls implementation is their need for big amount of water. A green wall may require 1 l/m^2 of drinking water daily in countries with cool climates (Mahmoudi et al., 2021; Xu et al., 2020). This could be tackled by using greywater as an alternative to purified

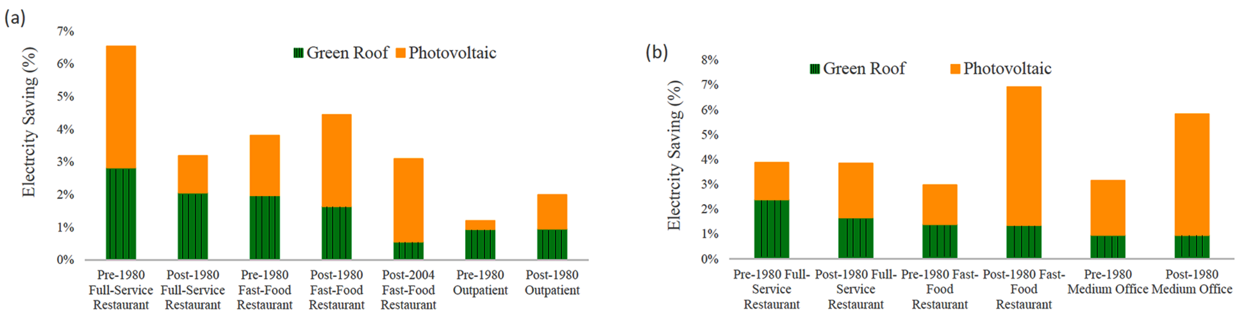

Figure 5. Percentage (%) of annual electricity savings from the integration of green roofs and photovoltaic systems compared with traditional roofs under the A1F1 emission scenario in 2050: a – Glendale; b – Koreatown (Zheng & Weng, 2020)

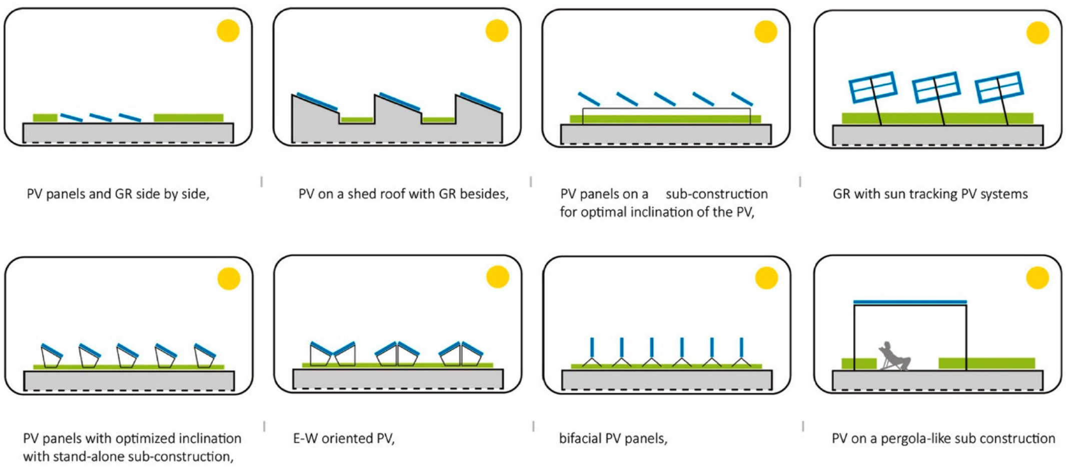

Figure 6. Possible combinations of PV panels and green rooftops, modified according to Pfoser (Zluwa & Pitha, 2021)

water to irrigate green roofs. Furthermore, green roofs acting as a biofilter system could serve as a solution for the treatment and refining of greywater (Mahmoudi et al., 2021; Xu et al., 2020), which could be regarded as a decentralized, environmental, and cost-effective treatment system that also limits subsurface infrastructure (Pradhan et al., 2019; Chang et al., 2011).

Conclusions

There is a lack of research in this study area in cold climate regions. However, it is still observable from this review that a PV-green roof is potentially advantageous in the substantiality of a building, the environment, the PV cell efficiency, and plant variation and condition compared to stand-alone PVs or only green roofs. The integration of PV and green roofs enhances the function's effectiveness in reducing a building's energy demands, even in harsh winters. The findings obtained from this review show that temperature-sensitive PV panels are suitable for implementation in countries with cold climates; it is of high importance to carefully select the plant species of the green roofs to make sure they would withstand the weather conditions (plant species such as Sedum are suitable to grow in cold countries and positively influence the green roof's vitality); greywater could be a reliable supply to irrigate the greenery on roofs; reusing greywater reduces water waste; and the green roof layers work as a filter which could be a cost-effective water-treatment system. Further studies are needed to analyse the performance of these findings when integrated in cold regions, to closely observe the feasibility and to have more solid experimental results proving it's practicability.

References

Ascione, F., Bianco, N., de' Rossi, F., Turni, G., & Vanoli, G. P. (2013). Green roofs in European climates. are effective solutions for the energy savings in air-conditioning? *Applied Energy*, *104*, 845–859. https://doi.org/10.1016/j.apenergy.2012.11.068

Bousselot, J., Slabe, T., Klett, J., & Koski, R. (2017). Photovoltaic array influences the growth of green roof plants. *Journal of Living Architecture*, *4*(3), 9–18. https://doi.org/10.46534/jliv.2017.04.03.009

Chang, N.-B., Rivera, B. J., & Wanielista, M. P. (2011). Optimal design for water conservation and energy savings using green roofs in a green building under mixed uncertainties. *Journal of Cleaner Production*, *19*(11), 1180–1188. https://doi.org/10.1016/j.jclepro.2011.02.008

Cubi, E., Zibin, N. F., Thompson, S. J., & Bergerson, J. (2015). Sustainability of rooftop technologies in cold climates: Comparative life cycle assessment of white roofs, green roofs, and photovoltaic panels. *Journal of Industrial Ecology*, *20*(2), 249–262. https://doi.org/10.1111/jiec.12269

De Gisi, S., Casella, P., Notarnicola, M., & Farina, R. (2015). Grey water in buildings: A mini-review of guidelines, technologies and case studies. *Civil Engineering and Environmental Systems*, *33*(1), 35–54. https://doi.org/10.1080/10286608.2015.1124868

Drücke, J., Borsche, M., James, P., Kaspar, F., Pfeifroth, U., Ahrens, B., & Trentmann, J. (2021). Climatological analysis of solar and wind energy in Germany using the Grosswetterlagen Classification. *Renewable Energy*, *164*, 1254–1266. https://doi.org/10.1016/j.renene.2020.10.102

Dubey, S., Sarvaiya, J. N., & Seshadri, B. (2013). Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the World – A Review. *Energy Procedia*, *33*, 311–321. https://doi.org/10.1016/j.egypro.2013.05.072

European Commission. (2019). Press corner. Building and renovating. https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6725

Evans, L. (2015, October 14). *Combining the benefits of solar – PV and green roofs. Organic Roofs*. https://www.organicroofs.co.uk/combining-the-benefits-of-solar-pv-and-green-roofs/?fbclid=IwAR1akbA1FeONamcfJNCG1i1cgZhlS2CpQF0B0wdlQb5JLBNIJAK_lItdwWI

Feng, C., Zheng, H., Wang, R., Yu, X., & Su, Y. (2015). A novel solar multifunctional PV/t/D system for green building roofs. *Energy Conversion and Management*, *93*, 63–71. https://doi.org/10.1016/j.enconman.2015.01.001

Hachem-Vermette, C., Cubi, E., & Bergerson, J. (2016). Energy performance of a solar mixed-use community. *Sustainable Cities and Society*, *27*, 145–151. https://doi.org/10.1016/j.scs.2015.08.002

Hoyer, W. (2022, November 3). Europe needs to forge ahead with Renewable Energy. *European Investment Bank*. https://www.eib.org/en/stories/renewable-energy-europe-africa

Hui, S. C. M., & Chan, S. C. (2011). *Integration of Green Roof and Solar Photovoltaic Systems*.

Johannessen, B. G., Hanslin, H. M., & Muthanna, T. M. (2017). Green roof performance potential in cold and wet regions. *Ecological Engineering*, *106*, 436–447. https://doi.org/10.1016/j.ecoleng.2017.06.011

Kamarulzaman, N., Hashim, S. Z., Hashim, H., & Saleh, A. A. (2014). Green roof concepts as a passive cooling approach in tropical climate- An overview. *E3S Web of Conferences*, *3*, 01028. https://doi.org/10.1051/e3sconf/20140301028

Lamnatou, C., & Chemisana, D. (2015). A critical analysis of factors affecting photovoltaic-green roof performance. *Renewable and Sustainable Energy Reviews*, *43*, 264–280. https://doi.org/10.1016/j.rser.2014.11.048

Lönnqvist, J., Blecken, G.-T., & Viklander, M. (2021). Vegetation cover and plant diversity on Cold Climate Green roofs. *Journal of Urban Ecology*, *7*(1). https://doi.org/10.1093/jue/juaa035

Mahmoudi, A., Mousavi, S. A., & Darvishi, P. (2021). Greywater as a sustainable source for development of green roofs: Characteristics, treatment technologies, reuse, case studies and future developments. *Journal of Environmental Management*, *295*, 112991. https://doi.org/10.1016/j.jenvman.2021.112991

Mansouri Kouhestani, F., Byrne, J., Johnson, D., Spencer, L., Hazendonk, P., & Brown, B. (2018). Evaluating solar energy technical and economic potential on rooftops in an urban setting: The City of Lethbridge, Canada. *International Journal of Energy and Environmental Engineering*, *10*(1), 13–32. https://doi.org/10.1007/s40095-018-0289-1

Mussard, M. (2017). Solar energy under cold climatic conditions: A review. *Renewable and Sustainable Energy Reviews*, *74*, 733–745. https://doi.org/10.1016/j.rser.2017.03.009

Pantic, L. S., Pavlović, T. M., Milosavljević, D. D., Radonjic, I. S., Radovic, M. K., & Sazhko, G. (2016). The assessment of different models to predict solar module temperature, output power and efficiency for NIS, Serbia. *Energy*, *109*, 38–48. https://doi.org/10.1016/j.energy.2016.04.090

Pradhan, S., Al-Ghamdi, S. G., & Mackey, H. R. (2019). Greywater recycling in buildings using living walls and green roofs: A review of the applicability and Challenges. *Science of The Total Environment*, *652*, 330–344. https://doi.org/10.1016/j.scitotenv.2018.10.226

Sailor, D. J., Elley, T. B., & Gibson, M. (2011). Exploring the building energy impacts of green roof design decisions – a modeling study of buildings in four distinct climates. *Journal of Building Physics*, *35*(4), 372–391. https://doi.org/10.1177/1744259111420076

Schade, J., Lidelöw, S., & Lönnqvist, J. (2021). The thermal performance of a green roof on a highly insulated building in a sub-arctic climate. *Energy and Buildings*, *241*, 110961. https://doi.org/10.1016/j.enbuild.2021.110961

Sheps, R., Golovinsky, P., Yaremenko, S., & Shchukina, T. (2021). New passive solar panels for Russian cold winter conditions. *Energy and Buildings*, *248*, 111187. https://doi.org/10.1016/j.enbuild.2021.111187

Simon, F. (2019, December 12). The EU releases its green deal. Here are the key points. *Climate Home News from Euractiv*. https://www.climatechangenews.com/2019/12/12/eu-releases-green-deal-key-points/

Tamma, P., Schaart, E., & Gurzu, A. (2019, December 12). Europe's green deal plan unveiled. In *POLITICO*. https://www.politico.eu/article/the-commissions-green-deal-plan-unveiled/

Tian, Z., Lei, Y., & Gu, X. (2017). Building energy impacts of simple green roofs in the hot summer and cold winter climate zone: Suzhou as a study case. *Procedia Engineering*, *205*, 2918–2924. https://doi.org/10.1016/j.proeng.2017.10.095

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and Trends. *Renewable and Sustainable Energy Reviews*, *57*, 740–752. https://doi.org/10.1016/j.rser.2015.12.119

Xing, Q., Hao, X., Lin, Y., Tan, H., & Yang, K. (2019). Experimental investigation on the thermal performance of a vertical greening system with green roof in wet and cold climates during winter. *Energy and Buildings*, *183*, 105–117. https://doi.org/10.1016/j.enbuild.2018.10.038

Xu, L., Yang, S., Zhang, Y., Jin, Z., Huang, X., Bei, K., Zhao, M., Kong, H., & Zheng, X. (2020). A hydroponic green roof system for rainwater collection and greywater treatment. *Journal of Cleaner Production*, *261*, 121132. https://doi.org/10.1016/j.jclepro.2020.121132

Zheng, Y., & Weng, Q. (2020). Modeling the effect of green roof systems and photovoltaic panels for building energy savings to mitigate climate change. *Remote Sensing*, *12*(15), 2402. https://doi.org/10.3390/rs12152402

Zirnhelt, H. E., & Richman, R. C. (2015). The potential energy savings from residential passive solar design in Canada. *Energy and Buildings*, *103*, 224–237. https://doi.org/10.1016/j.enbuild.2015.06.051

Zluwa, I., & Pitha, U. (2021). The combination of building greenery and photovoltaic energy production – a discussion of challenges and opportunities in design. *Sustainability*, *13*(3), 1537. https://doi.org/10.3390/su13031537