Green and cool roof choices integrated into rooftop solar energy modelling

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HIGHLIGHTS

- An adapted solar energy model estimates PV yield on sustainable rooftops.
- A practical energy balance model is developed to simulate roof surface temperature.
- Including simulated roof temperature into solar energy modelling improves accuracy.
- In Zurich, PVs on green and cool roofs can generate up to 4\% more than gravel roof.
- Reflectivity, thickness and thermal conductivity of the roof affect PV energy yield.

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ABSTRACT

Due to their cooling ability, sustainable roofing configurations, such as green and cool roofs, have the potential to increase solar panel yield, which is temperature dependent. However, the influence of sustainable roofing configurations on panel yield is not yet considered in rooftop photovoltaic (PV) planning models; thus, the significance of these integrated systems cannot be evaluated. In order to quantify the potential benefits of sustainable rooftops on solar energy, the first goal of this study is to develop a method that systematically accounts for roof surface characteristics in the simulation of PV panel energy yield. To do so, a rooftop energy balance model is linked with a physically-based solar energy model (the System Advisor Model, SAM) to quantify the energy yield of PV installations on sustainable roofing configurations. Roof surface temperatures are first estimated using non-linear energy balance equations, then integrated into a revised version of SAM to simulate energy yield. This new method improves the accuracy of PV yield simulations, compared to prior assumptions of roof surface temperature equal to ambient temperature. This updated model is used for the second goal of the study, to understand how four roofing configurations (black membrane, rock ballasted, white membrane, and vegetated) influence PV panel yield, which is currently not well understood in cooler climates. For a flat rooftop PV installation near Zurich, Switzerland (temperate climate), results show that, compared to a conventional roof, green roofs can increase annual PV energy yield, on average, by 1.8\%, whereas cool roofs can increase it by 3.4\%. For the case-study installation, an inverse correlation between the 95th-quantile roof surface temperature and the PV energy yield was identified; an increase of 1 °C leads to a 71 kWh reduction in energy yield per year. Overall, cool roofs outperform green roofs in terms of increases in PV energy yield; however, potential improvements of both systems are non-negligible, even in relatively cooler climate regions like Switzerland. By providing a systematic method to evaluate the influence of the roofing configuration on PV energy yield, solar energy planners are able to differentiate between the benefits of traditional and sustainable rooftop configurations - the first step towards the coupling of distributed energy and sustainable building systems. In the future, this integrated method could be used as part of a holistic evaluation of the environmental, economic, and social objectives of green and cool roofs, as well as, other infrastructure systems.

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1. Introduction

Sustainable roofing configurations, such as green or reflective roofs, have been shown to reduce the surface temperature of rooftops with respect to conventional roofs (e.g., black membrane or rock ballasted) [1,2]. Research has shown that, compared to darker roofs, daily peak surface temperatures are between 10 and 20 °C lower on vegetated, green roofs [1,3] and 15 to 25 °C lower on reflective, cool roofs [1,4,5]. This is due to their modified surface characteristics, such as albedo and emissivity [6], which reduce absorbed solar radiation and alter the rate of long-wave radiation remit to the atmosphere [7]. On green roofs, where vegetation and substrate are present [8], temperature reductions are also due to latent heat released as evapotranspiration (ET) [3], referred to as evaporative cooling, which reduces sensible heat [9]. Due to the reduction in surface temperature, these sustainable roofs have the potential to increase the yield of rooftop photovoltaic (PV) panels, whose conversion efficiency is temperature dependent [10]. For multicrystalline silicon modules, conversion efficiency is reduced by approximately 0.45% as cell temperature rises by 1 °C above the reference temperature (usually 25 °C) [11,12]. Thus, the roofing configuration, which influences the heat and energy fluxes exchanged between the roof and the PV panels, could play a considerable role in the panel conversion efficiency and ultimately, in the energy yield obtained from PV installations.

However, the influence of sustainable roofing configurations on PV panel yield is not yet considered in rooftop photovoltaic (PV) planning models; thus, the significance of these integrated systems is rarely evaluated without experimental campaigns. As summarized in review studies (e.g., [13,14]), results from experimental studies are promising, especially in warmer regions (e.g., Hui & Chan (2011) [15], Chemisana & Lamnatou (2014) [16], Osma-Pinto & Ordoñez-Plata (2019) [17]), supporting the need for integrated PV-sustainable roof evaluation methods. Monitoring studies and statistical analyses in warmer climates have shown that vegetated roofs combined with PV panels, referred to as integrated PV-green roof systems, can increase annual PV yield by 1.3% in Colombia [17], up to 3.3% in Spain [16], and as much as 8.3% in Hong Kong [15], compared to conventional roofs. In Spain, Chemisana & Lamnatou (2014) found that changing the vegetation type could further increase the annual energy yield by 1.3%. In cooler climates, results are limited, but tend to be modest. Compared to conventional roofs, experimental studies showed a maximum energy yield increase of 0.5% in Pittsburgh (USA) [18], 0.7% in Winterthur (Switzerland) [20], and 1.2% in Portland (USA) [19]. Using regression analysis, Nagengast et al. (2013) [18] found that the positive effect of PV-green roofs increases in regions with higher solar irradiance and number of days above 25 °C [18].

Less is known about the potential energy yield of reflective, cool roofs combined with PV panels, referred to as integrated PV-cool roof systems, especially in cold or mild climates. However, the limited results in warmer areas are again promising. An experimental study in the hot and dry climate of the United Arab Emirates found that integrated PV-cool roof systems increased annual rooftop PV yield between 5 and 10% [21], which is potentially higher than the yield from a PV-green roof system. However, the panel yield from PV-green roofs has yet to be compared to integrated PV-cool roof systems in the literature. As a result, it remains unclear how green roofs compare to cool roofs in terms of solar energy output, and which configuration, if either, should be implemented. These questions are integral in regions where the benefits of integrated PV systems may be less evident, such as cooler places with lower solar irradiance, as well as, humid climates where evaporative cooling is less effective [22].

There is thus a need for straightforward, integrated planning tools that can evaluate how the PV energy yield would change in different climate conditions for different rooftop configurations, especially between green and cool roofs. Current solar energy models (e.g., System Advisor Model [23], PVlib [24], PVSYST [25]) use energy and mass equations to simulate a range of PV configurations and climatic systems; however, they do not account for the contribution of the rooftop type on the surface temperature. For instance, the System Advisor Model, widely used by stakeholders to evaluate the feasibility of solar PV installations (as in e.g., [26–29]), assumes that the rooftop surface temperature is equal to ambient temperature. Assumptions like these do not enable the energy yield of PV systems on green and reflective roofs to be quantified or compared.

The first aim of this study is thus to develop a novel method that can be used by stakeholders to compare the energy yield of PV installations on different rooftop configurations, including traditional (black membrane or rock ballasted) and sustainable (green and reflective) roofs. We argue that an accurate integration of roof heat fluxes in the solar energy assessment is an important step to reduce the uncertainty around the benefit of sustainable coatings on the PV energy yield, supporting the development and dissemination of these technologies, as well as, approaches to decarbonize the building energy system to achieve the goal of climate neutrality (e.g., as in [30,31]). The second aim of this study is to use this integrated model to compare the simulated yield of solar panels on reflective roofs with other roof types - the first study to do so. This straightforward modeling framework appeals to an interdisciplinary scientific audience, which can apply and adapt the model for different disciplines (e.g., research in renewable energy, building energy and decarbonization, or urban resilience and planning).

The study is structured as follows: Section 2 presents the background information, data, and methods used to integrate a rooftop energy balance model into a modified version of the System Advisor Model (SAM). This section also describes the rooftop PV installation near Zurich (Switzerland) that was used for model validation and comparison of four different roof types (black, rock ballasted, green and cool roofs). Section 3 presents and discusses the results from the case study, exploring the differences between roof configurations with a sensitivity analysis, and discussing the implications, key parameters and model uncertainties. Section 4 concludes the study and offers insights for future research.

2. Methods and data

Conventional flat roofs, defined as impervious roofs with a low reflectance roof coating (black or rock ballasted), are compared to sustainable rooftop technologies (green and cool roofs) that can reduce roof surface temperature. In this study, two models were used to quantify the influence of the roofing configuration on rooftop PV energy yield, including (1) a modified version of the System Advisor Model (SAM [23]) used to simulate PV panel energy yield, and (2) a rooftop energy balance model used to estimate the roof surface temperature, which is given as input to the modified SAM version. Fig. 1 presents an overview of the workflow for this study, including the information required for and produced by these models (in red and white, respectively). This method is used to evaluate the influence of four different rooftop configurations (black, gravel, green and cool) on the electricity generation for a solar installation in Dübendorf, Switzerland.

2.1. System Advisor Model

SAM, an open source software, is widely used to evaluate the technical and economic feasibility of renewable energy installations (e.g., [23,26–29,32–35]). To model rooftop solar energy installations, SAM implements a set of physically-based equations to consider the heat fluxes between the PV modules and the roof surface, which accounts for the influence of roof surface temperature and albedo on PV panel power output. The power output \(P_{out} \) (Eq. (1)) is the product of available solar radiation \(I_o\) module area \(A_m\), and the panel conversion efficiency at operating conditions \(\eta_{oc}\), which depends on the panel cell temperature \(T_{oc}\) (Eq. (2), [36]).

\[
P_{out} = I_o A_m \eta_{oc} 
\]
Fig. 1. Overview of the workflow for this study, including modeling data inputs (in red), modeling outputs (in white), and models used (in blue).

\[ \eta_{\text{AC}} = \eta_{\text{ref}} \times (1 - \beta \times (T_{\text{cell}} - T_{\text{ref}})) \]  

(2)

where \( \eta_{\text{AC}} \) is the panel conversion efficiency at operating conditions [-], \( \eta_{\text{ref}} \) is the panel conversion efficiency at reference conditions (usually an irradiance of 1000 W m\(^{-2}\) and an ambient temperature of 25 \(^{\circ}\text{C}\) [-]), \( \beta \) is the temperature coefficient of the cell \([\text{C}^{-1}]\), \( T_{\text{cell}} \) is the cell temperature \([\text{C}]\), and \( T_{\text{ref}} \) is the ambient temperature at reference conditions \([\text{C}]\).

As shown in Eq. (2), higher cell temperatures decrease panel efficiency, because thermally excited electrons begin to dominate the temperature effect and forced (caused by air flow on the surface) convection \([\text{W m}^{-2} \text{K}^{-1}]\). \( T_{\text{cell}} \) is the temperature of the panel cell \([\text{K}]\) and \( T_{\text{back}} \) is the air temperature below the back of the panel \([\text{K}]\).

2.1.1. Panel cell heat transfer

PV cell temperature is a function of the energy fluxes exchanged between the ambient air and the panel and between the panel and the roof surface. When panel temperature is larger than the ambient air temperature, the roof surface releases convective and radiant heat \([\text{W m}^{-2}]\). This is often the case, since the surface temperature of conventional roofs can be significantly higher than ambient temperature \([\text{1}]\). In SAM, the heat transfer model developed by Neises et al. (2012) \([\text{37}]\) is used to model the convective and radiant heat fluxes exchanged between the PV panel, the air, and the roof surface, and finally to compute the cell temperature of the PV panel. The fluxes between the panel and the roof that are considered in the Neises model are shown in bold in Fig. 2.

The radiative heat flux between the panel and the roof is a function of their temperature gradient, as well as, the emissivity and view factor (Eq. (3)).

\[ \text{LW}_{\text{net,back}} = -\varepsilon_b \times F_{b-g} \times \sigma \times (T_{\text{cell}}^4 - T_{\text{back}}^4) \]  

(3)

where \( \text{LW}_{\text{net,back}} \) is the radiative heat flux on the panel back \([\text{W m}^{-2}]\), \( T_{\text{cell}} \) is the roof surface temperature \([\text{K}]\), \( T_{\text{back}} \) is the temperature of the panel cell \([\text{K}]\), \( \varepsilon_b \) is the emissivity of the backside of the panel [-], \( F_{b-g} \) is the view factor between back side and ground [-], and \( \sigma \) is the Stefan-Boltzmann constant \([\text{W m}^{-2} \text{K}^{-4}]\).

The convective heat flux (Eq. (4)) on the back of the panel is influenced by the temperature of the air on the panel back-side, which depends on the roof surface temperature, and the heat transfer coefficient (a function of wind speed, atmospheric pressure and air density \([\text{7}]\)).

\[ Q_{\text{H,back}} = -h_b (T_{\text{cell}} - T_{\text{back}}) \times (T_{\text{cell}} - T_{\text{back}}) \]  

(4)

where \( Q_{\text{H,back}} \) is the convective heat flux on the panel back \([\text{W m}^{-2}]\), \( h_b \) is the heat transfer coefficient, combined by free (caused by buoyancy effect) and forced (caused by air flow on the surface) convection \([\text{W m}^{-2} \text{K}^{-1}]\) \([\text{37}]\), \( T_{\text{cell}} \) is the temperature of the panel cell \([\text{K}]\) and \( T_{\text{back}} \) is the air temperature below the back of the panel \([\text{K}]\).

2.1.2. Accounting for changes in surface temperature

In the standard heat transfer model implemented in SAM, the surface temperature and the temperature on the back of the panel are assumed to be equal to the ambient temperature \([\text{37}]\). However, heat can be released from the ground surface when the roof surface temperature is higher than the ambient temperature, leading to an increase of the air temperature below the panel \([\text{38}]\). Moreover, the air on the back of the panel can be less ventilated and poorly mixed with the ambient air \([\text{39}]\). This assumption, which implies that no heat is exchanged between the roof surface and the air, underestimates the radiative and conductive heat fluxes towards the solar panel, since the roof surface temperature can be higher than the ambient temperature \([\text{1}]\), especially during the radiation peak at noon. As a result, PV cell temperature may be underestimated, leading to an overestimation of the PV power output (see Eq. (1)).

To quantify the influence of sustainable roof coatings on rooftop PV energy yield, the open source version of the SAM heat transfer model was adapted. A surface temperature timeseries is given as input to the model, replacing the standard assumption that roof surface temperature is equal to ambient temperature. The model used to simulate the roof surface temperature timeseries is described in Section 2.2.

To delineate the amount of convective heat flux that reaches the panel, it is assumed that the air temperature behind the panel \( T_{\text{back}} \) has a value between ambient temperature and roof surface temperature, according to the temperature factor \( f_{\text{back}} \) (Eq. (5)). The panel back-side air temperature \( T_{\text{back}} \) computed in Eq. (5) is then used to compute the...
adapted convective heat flux (Eq. (4)).

\[ T_{\text{back}} = (T_{\text{amb}} - T_s) f_{\text{conv}} + T_s \]  

(5)

where \( T_{\text{back}} \) is the air temperature on the panel back [°C], \( T_{\text{amb}} \) is the ambient air [°C], \( f_{\text{conv}} \) is the temperature factor [-] and \( T_s \) the roof surface temperature [°C].

The temperature factor (\( f_{\text{conv}} \)) quantifies how well the air behind the panel is mixed, which is specific to the PV installation. This factor, which depends on the distance between the panels and the roof, the slope of the panels, and the ventilation on the roof, is an empirical value that should be calibrated for each PV installation. For instance, if \( f_{\text{conv}} \) is equal to 0, the air behind the PV panel (\( T_{\text{back}} \)) is equal to the surface temperature, signifying no mixing. On the other hand, if \( f_{\text{conv}} \) is equal to 1, the back of the panel is well ventilated and the temperature is in equilibrium with the ambient air, which is the standard SAM assumption. This approach was developed to compare the influence of different roof types on the power output of a single PV installation; however, further research would be needed to identify different \( f_{\text{conv}} \) values in order to consistently compare the output of PV installations with different design characteristics.

2.2. Rooftop energy balance model

An energy balance model was used to simulate the roof surface temperature. The roof is modeled as two uniform layers, including a bottom concrete layer that is covered by a top layer, which consists of either membrane (black or cool roofs), gravel (rock ballasted), or soil (green roof). The unknowns of the system are the roof surface temperature (\( T_{\text{roof}} \)) and the temperature between the two layers (\( T_{\text{roof}} \)) (Fig. 2), which are assumed to be uniform across the roof area (525 m² for the case study installation; see Table 2). The system of non-linear equations to obtain the unknowns is computed with the fsoeve function in Matlab [40].

Eq. (6) represents the energy balance for the top layer, accounting for: net shortwave (SW_{\text{net}}) and longwave (LW_{\text{net}}) radiation; convection composed of sensible (\( Q_s \)) and latent heat (\( Q_e \)) fluxes; conductive heat (\( Q_{\text{cond}} \)); and energy stored in the roof (\( \Delta S \)), all expressed in W m⁻². The energy balance of the bottom layer only considers the conductive heat flux and the heat stored in the roof (last two terms of Eq. (6)).

\[ SW_{\text{net}} + LW_{\text{net}} + Q_s + Q_e + Q_{\text{cond}} = \Delta S \]  

(6)

Incoming shortwave solar radiation (\( SW_{\text{in}} \)) is the main source of energy on the roof, which includes both direct (\( E_0 \)) and diffuse (\( E_d \)) radiation. Reflected shortwave radiation (\( SW_{\text{ref}} \)) is computed as a fraction of incoming solar radiation (\( SW_{\text{in}} \)), based on the surface albedo (\( \alpha \)) [-] (Eq. (7)).

\[ SW_{\text{net}} = SW_{\text{in}} (1 - \alpha) \]  

(7)

The net radiative heat flux (\( LW_{\text{net}} \)) (incoming flux - outgoing flux) is computed according to the temperature gradient of the roof surface and sky, shown in Eq. (8).

\[ LW_{\text{net}} = \varepsilon \sigma (T_{\text{roof}}^4 - T_{\text{sky}}^4) \]  

(8)

where \( \varepsilon \) is the roof emissivity [-], \( \sigma \) is the Stefan-Boltzmann constant [W m⁻² K⁻⁴], \( T_{\text{roof}} \) is the roof surface temperature [K] and \( T_{\text{sky}} \) is the sky temperature [K], which is calculated as a function of the dew point temperature (\( T_{\text{dew}} \)), as performed in SAM [37] (Eq. (9)).

\[ T_{\text{dew}} = T_{\text{amb}} + \frac{0.711 + 0.0056 T_{\text{dew}} + 0.000073 T_{\text{dew}}^2 + 0.013 \cos(t)^{0.25}}{0.511} \]  

(9)

where \( T_{\text{sky}} \) is the sky temperature [°C], \( T_{\text{amb}} \) is the ambient temperature [°C], \( T_{\text{dew}} \) is the measured dew point temperature [°C], and \( t \) is the hour of the day [-].

The convective heat flux (\( Q_s \)) is computed according to Eq. (10), considering the temperature gradient between the roof surface and ambient air. The heat transfer coefficient (\( \overline{h}_c \)) is computed following the methodology used by Neises et al. (2012) [37], and adapted for a heated upward, horizontal roof.

\[ Q_s = -\overline{h}_c (T_s, T_{\text{Amb}}) (T_s - T_{\text{amb}}) \]  

(10)

The conductive heat flux (\( Q_{\text{cond}} \)) is computed for the two roof layers, according to the temperature gradient between surface temperature (\( T_s \)) and roof temperature (\( T_{\text{roof}} \)) for the top layer, and between roof temperature (\( T_{\text{roof}} \)) and indoor temperature of the building (\( T_{\text{in}} \)) for the bottom layer [41]. Eq. (11) shows the calculation of the conductive heat flux on the top layer.

\[ Q_{\text{cond}} = \lambda \frac{(T_{\text{roof}} - T_s)}{z} \]  

(11)

where \( \lambda \) is the thermal conductivity of the roof material [W m⁻¹ K⁻¹], \( T_s \) is the roof surface temperature [K], \( T_{\text{roof}} \) is the temperature between the two roof layers [K] and \( z \) is the thickness of the roof layer [m].

The temperature inside the building (\( T_{\text{in}} \)) is assumed to be regulated by a heating and cooling system, according to de Munck et al. (2018) [42]. When the ambient temperature is lower than 19 °C, the indoor temperature of the building is assumed to be heated up to 19 °C. When the ambient temperature is greater than 26 °C, the cooling system is assumed to keep the temperature at 26 °C. If the ambient temperature is between 19 and 26 °C, then the temperature inside the building is equal to the ambient temperature.

The heat stored in the roof (\( \Delta S \)) is computed as in Meili et al. (2020) [41] and shown in Eq. (12). The stored heat is computed for both roof layers.

\[ \Delta S = C_p s \frac{\rho \gamma z}{dt} \Delta T_{\text{roof}} \]  

(12)

where \( C_p \) is the specific heat capacity of the roof material [J kg⁻¹ K⁻¹], \( \rho \) is the roof material density [kg m⁻³], \( z \) is the roof thickness [m], \( \Delta T_{\text{roof}} \) is the roof layer temperature difference between the current and the previous time step [K].

The latent heat flux (\( Q_e \)) is calculated in two parts: as crop evapotranspiration (ETc) present only on green roofs and as evaporative cooling (EC) from depression storage, present on all roof types. ETc is computed using the FAO Penman-Monteith (P-M) reference equation [43], widely used for modeling ET, shown in Eq. (13).

\[ ET_c = k_c \frac{0.408 \Delta (R_{\text{net}} - Q_s) + \gamma \frac{R_{\text{net}}}{\rho \gamma z} (e_r - e_s)}{\Delta + \gamma (1 + 0.34 \Delta)} \]  

(13)

where \( R_{\text{net}} \) is net radiation (\( SW_{\text{in}} + LW_{\text{net}} \) [W m⁻²]), \( Q_{\text{cond}} \) is the conductive heat flux [W m⁻²], \( \gamma \) is the psychrometric constant [kPa °C⁻¹], \( T_{\text{amb}} \) is the air temperature at 2 m height [°C], \( e_r \) is the saturation vapor pressure [kPa], \( u_2 \) is the wind speed at 2 m height [m s⁻¹], \( e_s \) is the actual vapor pressure [kPa], \( \Delta \) is the slope of the relationship between saturation vapor pressure and temperature [kPa °C⁻¹], and \( k_c \) is the crop coefficient of the green roof vegetation [-]. Eq. (13) computes the reference evapotranspiration of a hypothetical crop, which represents uniform green grass growing without water limitations [44], multiplied by the crop coefficient (\( k_c \)), which represents the integration of four vegetation characteristics into a single coefficient (height, albedo, canopy resistance, and vegetation coverage) [44], accounting for the type of vegetation present on the green roof.

The latent heat used by water to evaporate directly from the roof surface (EC) is computed according to Eq. (14) [41]. EC is limited by the potential evaporation (PET), which depends on air density, saturated specific humidity, actual specific humidity, saturation vapor pressure and actual vapor pressure (see Section A1 in the Appendix). The enthalpy of vaporization (\( \Delta H_{\text{sf}} \)), which depends on the ambient temperature (\( T_{\text{amb}} \)), is computed in Eq. (15). The available water for evaporation is equal to the observed precipitation (\( P \)) times the percentage of water retained by the roof, referred to as the ponding factor (\( f_{\text{pond}} \), plus...
any surplus of ponded water from the previous timestep ($W_p$).

$$EC = \begin{cases} \Delta H_{\text{vat}} \frac{f_{\text{vat}} + P_i + W_p}{1000 \, \text{dt}} \rho_{\text{w}}, \text{EC} < \text{EC}_{\text{POT}} \\ \text{EC}_{\text{POT}}, \text{EC} \geq \text{EC}_{\text{POT}} \end{cases}$$

(14)

$$\Delta H_{\text{vat}} = 1000 \times (2501.3 - 2.361 \times T_{\text{amb}})$$

(15)

where $EC$ is the latent heat flux [W m$^{-2}$], $\Delta H_{\text{vat}}$ is the enthalpy of vaporization [J kg$^{-1}$], $f_{\text{vat}}$ is the ponding factor [-], $P_i$ is the observed precipitation at timestep $i$ [mm], $W_p$ is the ponded water surplus from the previous timestep [mm], $dt$ is the calculation timestep [s], $\rho_{\text{w}}$ is the density of the water [kg m$^{-3}$], $\text{EC}_{\text{POT}}$ is the potential latent heat flux (limited by potential evaporation, Eq. A1 in the Appendix) [W m$^{-2}$] and $T_{\text{amb}}$ is the ambient temperature [$^\circ$C].

In addition to the energy fluxes, shading on the roof is accounted for by introducing a factor that reduces the incoming shortwave solar radiation ($SW_{\text{rof}}$) on the roof, defined as a roof view factor ($f_{\text{roof}}$). This factor, developed by Scherba et al. (2011) [1], represents the average reduction of shortwave incident radiation on the PV shaded roof. This parameter is eventually calibrated with measured data (see Section 2.4.1). Finally, the influence of downward solar panel radiative heat towards the roof surface is not considered since it is relatively small compared to the other fluxes.

2.3. Modeling data requirements

Table 1 summarizes the weather data and the roof parameters required by the models used in this study (rooftop energy balance model, the P-M model and SAM). The weather data (listed as columns in the top of Table 1) were collected at the MeteoSwiss station in Kloten [45], and are given to the models in a hourly timescale. The inputs to the energy balance model are assumed to be uniform across the spatial resolution of the model, i.e., the roof area (525 m$^2$ for the case study installation; see Table 2).

The parameters (listed as columns in 5th row of Table 1) describe the roof characteristics and material proprieties. Surface albedo ($\alpha$), which represents the capacity of a material to scatter incoming solar radiation, is dependent on the roof color, or in case of green roofs, on the vegetation type, density and groundcover [46]. The emissivity ($\epsilon$) describes the effectiveness of the material to emit energy as thermal radiation [47], which influences the amount of radiative heat released by the roof ($LW_{\text{Roof}}$). Thermal conductivity ($\lambda$), used to compute the conductive heat ($Q_{\text{cond}}$), measures the ability of a solid material to conduct heat [48]. Heat capacity ($C_p$), defined as the amount of heat required to produce a unit change in temperature for a given mass of material, influences the heat stored ($\Delta S$) in the roof layer [49]. When vegetation is present (as in the green roof configuration), the crop coefficient ($k_c$) is used to account for the vegetation type (Eq. (13)) [44]. Thickness ($z$), thermal conductivity ($\lambda$), heat capacity ($C_p$), and density ($\rho$) are specific to each roof layer, and therefore considered for both top and bottom layers. In total, to describe both roof layers in the roof energy balance model, a set of 14 parameters is required.

2.4. Model calibration and validation

A rooftop solar panel installation located at the EMPA campus in Dübendorf, Switzerland (47.4° N, 8.61° E, 440 m.a.s.l.) is used to calibrate parameters for a conventional, rock ballasted roof configuration. This roof is also used to validate the rooftop energy balance model and the adapted SAM model. The installation consists of 156 silicon PV panels with a slope of 13°, over a flat roof area of 525 m$^2$. Technical information about the installation is listed in Section A.3 in the Appendix. A green roof located 500 m from the rock ballasted roof was used to calibrate parameters for the green roof configuration (see Appendix Section A.2).

| Variable | Date | Diffuse horizontal irradiance [W m$^{-2}$] | Global horizontal irradiance [W m$^{-2}$] | Dry-bulb temperature [°C] | Dew point temperature [°C] | Atmospheric pressure [hPa] | Wind direction [°] | Wind speed [m s$^{-1}$] | Precipitation [mm] | Vapor pressure [hPa] | Growth factor | Crop evaporation [W m$^{-2}$] | Relative humidity [%] | Albedo [-] | Solar panel inclination [°] | Roof area [m$^2$] | Elevation of the location [m a.s.l.] | Solar panel orientation [-] | Ground cover [-] |
|----------|------|------------------------------------------|------------------------------------------|---------------------------|---------------------------|----------------------------|--------------------------|------------------------|---------------------|------------------|-----------------|--------------------------------|------------------------|-------------|-------------------------------|-----------------|-----------------------------|---------------------|------------------|
| REB      | SAM  | P-M model                                | SAM                                      | REB                       | SAM                       | P-M model                  | REB                      | SAM                    | P-M model           | SAM              | P-M model        | SAM              | P-M model                  | REB                      | SAM          | P-M model                      | SAM              | P-M model                   | SAM               | P-M model               |

Table 1: Input weather and parameters required by the rooftop energy balance model (REB), the Penman-Monteith evapotranspiration model (P-M), and the solar energy model (SAM).
2.4.1. Energy balance model calibration

The rooftop energy balance model was calibrated by comparing the simulations to the roof surface temperature observations. These values were measured with a FLIR C3 infrared camera between the 3rd and 7th of August 2020 on the case study gravel roof and on a green roof in Dübendorf, Switzerland (Section A2 in the Appendix).

Fig. 3 shows the visual comparison of the roof surface temperature for the rock ballasted (top panel in Fig. 3) and green (bottom panel in Fig. 3) roof. The ambient temperature is also provided for reference (red dashed line). Due to rainfall and cloud cover on the first two days (hours 0–48), ambient air temperature and surface temperature are low in comparison to the following three days where there was full sun.

A visual assessment combined with an evaluation of several goodness of fit measures (GOF) was used to calibrate the roof energy balance model. To quantify the error, GOF measures were computed, including root mean square error (RMSE), mean biased error (MBE), squared correlation coefficient ($r^2$) and total error (see description in Table A5 in the Appendix). The RMSE for the entire week was initially minimized simultaneously using optimization; however, despite leading to slightly higher error, a visual assessment was ultimately selected for calibration. Reducing the error through visual comparison enables the simulation to more accurately reflect the peak temperature on sunny, higher heat days, which are more relevant for PV panel performance, since PV electricity output is more sensitive to temperature changes during days with high solar radiation (see Section 2.4.2). The final parameters, which were calibrated simultaneously, are summarized in Table 2 (see Section 2.5).

| Parameter | Black roof | Gravel roof | Green roof | Cool roof |
|-----------|------------|-------------|------------|-----------|
| Roof area $[m^2]$ | 525 (160–1500) [53] | 0.22 (0.20–0.30) [54] | 0.30 (0.20–0.35) [46] | 0.70 (0.50–0.85) [1] |
| Albedo [-] | 0.06 (0.03–0.15) [1] | 0.90 (0.85–0.95) [1] | 0.90 (0.85–0.95) [1] | 0.92 (0.85–0.95) [1] |
| Emissivity [-] | 0.91 (0.85–0.95) [1] | 0.85 (0.6–0.95) [1] | 0.50 (0.1–0.75) [56] | 0.85 (0.6–0.95) [1] |
| Roof view factor [-] | 0.85 (0.6–0.95) [1] | 0.85 (0.6–0.95) [1] | 0.85 (0.6–0.95) [1] |
| Ponding factor [-] | 0.20 (0–0.30) | 0.20 (0–0.30) | 0.14 (0–0.30) | 0.20 (0–0.30) |
| Crop coefficient [-] | – | – | 0.60 (0.3–1.2) [43] | – |
| Top layer | | | | |
| Roof thickness [m] | 0.004 (0.0015–0.005) [51] | 0.06 (0.03–0.10) [53] | 0.125 (0.05–0.20) | 0.0005 (0.0001–0.001) [4] |
| Thermal conductivity [W m$^{-1}$ K$^{-1}$] | 0.50 (0.20–0.60) [55] | 1.44 (0.40–1.60) [55] | 1.73 [55] (0.25–2.20) [52] | 0.045 (0.01–0.1) [4] |
| Heat capacity [J kg$^{-1}$ K$^{-1}$] | 1000 (800–1100) [55] | 881 (200–1000) [55] | 837 (800–2000) [55] | 0 (0–100) [4] |
| Density [kg m$^{-3}$] | 1700 (700–2200) [55] | 1674 (1000–2200) [55] | 1842 (800–2000) [55] | 1053 (900–1100) [4] |
| Bottom layer | | | | |
| Roof thickness [m] | 0.28 (0.15–0.40) [53] | 1.14 (0.08–1.51) [52] | 985.7 (800–1000) [55] | 1850 (320–2400) [52] |
| Thermal conductivity [W m$^{-1}$ K$^{-1}$] | | | | |
| Heat capacity [J kg$^{-1}$ K$^{-1}$] | | | | |
| Density [kg m$^{-3}$] | | | | |

Fig. 3. Visual comparison of the roof surface (solid line) and ambient (dashed line) temperature timeseries with respect to the observations (markers), for the rock ballasted (top panel) and green roof (bottom panel).
potential of the green roof relative to the gravel roof (green line in right panel is lower than the grey line in left panel in Fig. 3). Moreover, Fig. 3 reinforces that the roof surface temperature differs considerably from the ambient temperature, especially on sunny days (hours 48–120). The peak surface temperature surpasses ambient temperature by approximately 25°C on the gravel roof and 10°C on the green roof.

There are, however, still limitations that could be addressed to reduce the error. For instance, in both roofing configurations, the rooftop energy balance model better represents the daily surface temperature profile on hot and sunny days. This is partially due to the calibration method, but there is also evidence that variations are not only due to roof surface temperature simulations. In fact, Fig. 4 (presented in Section 2.4.2) shows that the power output is similar for all temperature factor \( f_{\text{conv}} \) values during the first two rainy days, meaning that the error on cold days is not due to the roof surface temperature, since low ambient temperatures will not strongly influence the cell temperature. Thus, the variation between the adapted SAM version and the observed values is likely due to the variability of rain and cloud cover between the observed data at the weather station and the actual weather on site, since the weather station lies approximately 7 km away from the PV installation. This distance leads to systematic differences in solar radiation and precipitation between the study site and weather station that may reduce the accuracy of the simulations. However, as discussed previously, PV performance on cloudy days is not as relevant as performance on sunny days. Although it is difficult to reduce errors due to variability in rain and cloud cover, a longer measurement period for calibration could potentially improve the model error. However, due to the relevance of the summer conditions and the scope of the paper, the calibration period of one week in summer, which is consistent with other studies in this field (e.g., Scherba et al. [1]), is adequate for the purposes of this study.

### 2.4.2. SAM model calibration

The surface temperature measurements of the gravel roof were given as input to the adapted SAM model to calibrate the temperature factor \( f_{\text{conv}} \), which represents the difference in temperature between the air on the back of the panel and the roof surface.

Fig. 4 presents the difference between the measured power output at the inverter and the simulated PV panel power output from the SAM model using: (1) ambient temperature as roof surface temperature, (2) \( f_{\text{conv}} \) of 0 (representing the air on the back of the panel is equal to the roof surface temperature), (3) \( f_{\text{conv}} \) of 0.1 (the best fit), and (4) \( f_{\text{conv}} \) of 1 (representing the air on the back of the panel is equal to ambient temperature). Lower errors occur when the markers are close to 0 (horizontal black line). For further information, Fig. A5 in the Appendix presents the visual comparison of the GOF measures and Table A6 shows the exact GOF values for different \( f \)-factor values (0, 0.1, 0.2, 0.5 and 1).

The adapted SAM model reproduces the observed PV output most closely with \( f_{\text{conv}} \) values that are lower than 0.5. This means that the air temperature on the panel back is closer to the roof surface temperature than to the ambient air temperature, which is consistent with the PV installation design. In fact, the panels are close to the roof surface and poorly ventilated, which leads to a relevant convective heat flux from the roof to the panel (see Section A2 in the Appendix). The temperature factor that minimizes the total error, which is defined as the sum of errors divided by the total energy yield, has a value of 0.1. In Fig. 4, the yellow points are closer to 0 when the simulations overestimate the power output (above the black line). On the other hand, when the simulations underpredict the power output, higher \( f_{\text{conv}} \) values improve the performance. Overall, an \( f_{\text{conv}} \) value of 0.1 minimizes the total error, which is equal to 0.03%. Therefore, the remaining simulations are performed with an \( f_{\text{conv}} \) value equal to 0.1. Using the calibrated rooftop energy balance output, the SAM model was validated for the gravel roof configuration on a daily time scale for the year 2019 (results shown in Section 3.1).

### 2.5. Rooftop configuration scenarios

After the model validation, the parameter sets of three additional roofing configurations were analyzed, including a conventional roof (bituminous dark) and two sustainable roofing configurations (green roof and cool roof with a white membrane), summarized in Table 2. Parameters in bold were calibrated using visual inspection and goodness of fit (GOF) measures (see Section 2.4.1), while the other parameter values were either selected from the literature, obtained from building plans or assumed based on materials available on the market (source in brackets). The baseline values for the black roof were assumed according to consumer information for bituminous membranes [50,51], while green and cool roof parameters were sourced from the literature [1,4,43,46,52].

Architectural roof plans provide information about the gravel roof layers, which consist of a concrete bottom layer (0.18 m thickness), an
insulation layer (0.10 m thickness) and a gravel top layer (between 0.04 and 0.06 m thickness). The bottom layer is modeled as a combination of the concrete and insulation layers, with properties that are the weighted average (considering the layer thickness) of the two materials. The bottom layer has the same parameter values for all roof types, meaning that only the top layer is changing.

All properties are the same in both the rooftop energy balance and the SAM model, except the emissivity of the roof surface, which could not be modified in the SAM source code, since it would require a modification of the iterative solver of the heat transfer model [37]. In SAM, the emissivity of the roof surface is instead equal to the panel back emissivity (ε = 0.7).

The parameter sets were used to simulate the roof surface temperature of the different roofing configurations, which were finally given as input to the validated, adapted SAM model to compute the respective annual solar energy yield. The baseline values are used to obtain the main results, while the upper and lower parameter bounds are used to perform a sensitivity analysis, in order to identify which roof properties are most relevant for the PV installation energy yield. The parameter range was obtained from literature values and from assumptions. In the sensitivity analysis, just one parameter at the time was modified, testing both upper and lower bounds, while the other parameters were taken from the baseline parameter set. This led to 29 parameter sets for the green roof configuration, and 27 sets for the other configurations, since they do not have the crop coefficient, which describes the vegetation.

3. Results and discussion

3.1. SAM model validation

Fig. 5 presents the visual comparison between the simulated and observed power output for the standard and the adapted SAM version for the gravel roof installation in 2019. The adapted SAM model uses the simulated roof surface temperature from the rooftop energy balance model, whereas the standard SAM version assumes roof surface temperature is equal to ambient temperature. These simulation values are plotted against the observations, and a fitting line between simulations and observations for both SAM versions is also shown. The thin, black line represents the ideal fit, where the simulations would be equal to the observations.

Both the standard and adapted SAM models tend to overestimate the energy yield throughout the year (red and grey lines are above the black line), especially on days with high energy output (sunny days). This supports the hypothesis that roof surface temperature has an influence on power output, which leads to an overestimation of the simulated energy yield. However, simulations using ambient temperature as roof surface temperature (standard SAM assumption) overestimate power output more than simulations using the estimated surface temperature (adapted SAM version). This overestimation is likely due to the fact that the roof surface temperature is considerably higher than ambient temperature on hot and sunny days (as described in subsequent sections and in the literature, e.g., [1,3]).

The overall error for the adapted SAM version is 7.8%, which is larger than the model accuracy of +/- 3% reported in the validated SAM report [32]. This difference could be due to the distance of 7 km between the installation in Dübenhorst and the weather station in Kloten, discussed in Section 2.4.1. Another reason for the higher error with respect to the SAM validation report could be due to the other parameters required by the SAM model that were not calibrated in this study, including shading, energy losses (DC/AC transformation) and module degradation rate. These values were taken from the standard SAM assumptions since no data for the case study installation was available (exact parameter values are listed in Table A2 in the Appendix).

A more accurate calibration may reduce the overestimation; nevertheless, the adapted SAM version is able to simulate the power output of the rooftop PV installation with better accuracy than the standard SAM model used in this study, reducing the total error from 12.0% to 7.8% (see Table A7 in the Appendix for additional GOF values). Accounting for the surface temperature in solar energy modeling can thus improve the accuracy of PV energy yield simulations, compared to the common modelling assumption that surface temperature is equal to ambient temperature.

3.2. Seasonal and diurnal patterns for different roofing configurations

Fig. 6 summarizes the average, daily profiles of the simulated roof surface temperatures (top panels) and difference in average power output (bottom panels) between the gravel roof and the other roofing configurations. The data are grouped by cold months, October to March (left), and warm months, April to September (right).

The roof surface temperature (top panel) generally follows a diurnal cycle linked to the incoming solar radiation on the roof. Interestingly, simulated surface temperatures of all roof types are higher than the ambient temperature during both cold and warm months. However, during the cold months, solar radiation is significantly lower, thus surface temperatures are lower overall and differences between the different roofing configurations are also small (less than 10 °C). On the other hand, during warm months, differences between the surface temperature profiles are higher (up to 20 °C).

As expected, daily peak temperatures are lower for sustainable roofing configurations than for conventional roofs. The cool roof has the lowest daily peak temperature (24 °C degrees in warm months, on average) and the flattest diurnal profile. The green roof has a slightly higher daily peak temperature (30 °C degrees in warm months, on average) than the cool roof; however, the peak surface temperature is still lower than the temperature on conventional roofs by about 10 °C, in warm months. The black and gravel roofs have similar temperature profile magnitudes. However, the black roof peak temperature occurs later in the day, similar to what can be observed on the cool roof. This is likely due to the reduced thickness of the top layer in black and cool roofs, which leads to higher conductive heat that warms up the concrete (bottom) layer first, and subsequently the top layer. Thus, the temperature peak between the black and gravel roof is similar (40 °C degrees in warm months, on average), despite the fact that the gravel roof has a larger albedo and was expected to be cooler than the black roof. This means that the thickness and the thermal conductivity of the roof have a large influence on surface temperature.

These findings highlight that roof surface temperatures between
different roofing configurations can vary considerably in summer, especially at noon, when the daily peak in solar radiation occurs and the potential to generate electricity from solar energy is maximized. Although it is not the focus of this study, the roof surface temperature is also relevant for thermal comfort in buildings, energy demand for cooling and heating systems and urban heat mitigation [1,57]. In summer, sustainable roofs could reduce outdoor temperature in proximity to the roof and stabilize indoor temperature due to improved building insulation [58].

As expected, the diurnal energy yield follows the surface temperature profile (Fig. 6, bottom panels), as do the differences in the energy yield between the configurations. During cold months, hourly differences are small (less than 0.3 kW) because differences in surface temperature between the roof types are smaller, and because less solar radiation is available in autumn and winter due to the tilt of the Earth’s axis. Autumn and winter in Zurich are also relatively cloudy, which further reduces incoming solar radiation and differences in surface temperature between roofing configurations. Consistent with surface temperature, differences in electricity generation are higher during warm months (up to 1 kW). This indicates that the rooftop configuration is likely more relevant for PV output in warmer regions, which is confirmed with other findings in the literature (e.g., [15–17]). However, simulation models should be used in these regions to confirm this hypothesis, as the cooling potential of green roofs is often questioned in warm and dry climates, since the required irrigation energy demand could compensate the PV energy yield increase [59].

3.3. Annual energy yield and uncertainty

In addition to seasonal variability in PV yield, the roofing configuration also leads to annual differences in energy output. Fig. 7 presents the annual energy yield of the baseline roofing configuration scenarios (colored bar) and the maximum and minimum energy yield (error bars) obtained through the sensitivity analysis (see Section A.5 in Appendix). For comparison, the energy yield obtained with the standard SAM version (using ambient temperature) is shown in red and the changes relative to the baseline gravel roof energy yield are illustrated on top of the bars.

Relative to the gravel roof baseline, a sustainable roofing configuration could increase the annual energy yield in Zurich by 1.8% for a green roof, and by 3.4% for a cool roof, on average. These results also show that accounting for the roofing configuration surface temperature reduces the expected energy yield relative to the assumption that temperature below the panels is equal to ambient temperature. With this
improve PV yield. There are currently no results reported in the literature suggesting that cool roofs would be better suited than green roofs to improve PV yield, compared to the black and gravel roofs. Depending on the design parameters selected, these results show that the potential increase in yield from PV-green roof systems is larger than previously established values for cooler regions (e.g., 0.5% [18] to 1.2% [19]). Due to variations in annual weather conditions, PV panels, installation designs, and vegetation, it is difficult to make a direct comparison; nevertheless, these results show that the potential increase in yield from PV-green roof systems is larger than previously established values for cooler regions. For reflective roofs, the 3.4% increase in annual yield reported in this study is larger than previously established values for cooler regions. For reflective roofs, the 3.4% increase in annual yield reported in this study is larger than previously established values for cooler regions. For reflective roofs, the 3.4% increase in annual yield reported in this study is larger than previously established values for cooler regions.

The potential increase of 1.8% for the integrated PV-green roof system is within the range reported in the literature for warmer regions (e.g., 1.3% [17] to 8.3% [15]); however, it is higher than the range reported for cooler regions (e.g., 0.5% [18] to 1.2% [19]). Due to variations in annual weather conditions, PV panels, installation designs, and vegetation, it is difficult to make a direct comparison; nevertheless, these results show that the potential increase in yield from PV-green roof systems is larger than previously established values for cooler regions. For reflective roofs, the 3.4% increase in annual yield reported in this study is larger than the yield obtained from PV-green roof systems, suggesting that cool roofs would be better suited than green roofs to improve PV yield. There are currently no results reported in the literature for reflective roofs in cooler regions; however, the findings in this study are lower than the range of 3 to 10% observed in the United Arab Emirates (UAE) [21]. This is, however, consistent with the conclusion from Nagengast et al. (2013) [18] that areas with higher solar irradiance (e.g., the UAE) will have higher gains in energy yield from sustainable roof types than areas with lower solar irradiance (e.g., Switzerland).

Put into context for the electricity demand of an average, four person Swiss household (equal to 5000 kWh/year [60]), the surplus electricity simulated in the case study could represent approximately 15% and 28% of the annual household electricity consumption, respectively for green and cool roofs. On a national level for Switzerland, assuming that all of the solar energy generated in Switzerland in 2015 (1761 GWh [61]) was from PV installations on conventional rooftops, switching to green roofs would produce, on average, 32 GWh more electricity per year and a switch to cool roofs, 60 GWh more per year. Considering that the rooftop PV energy capacity is predicted to grow in the future [62], these energy yield improvements could potentially increase the share of electricity generated from renewables, which is an important step to achieve the goal of climate neutrality [63].

While the previous section discussed average differences in PV yield between the different roof configurations, this section highlights the variability in these average values to the different design parameters using sensitivity analysis. The range of values used in this analysis are shown in Table 2. To allow for comparison, the annual PV yield for different roof configurations and parameters sets (i.e., scenarios) are compared to the 95th-quantile of the simulated annual surface temperature for each of these sensitivity scenarios. The 95th-quantile was selected because it better represents surface temperatures in warmer months, where the influence of sustainable roofs on PV yield was found to be higher (see Section 3.2). In Fig. 8, the 95th-quantile of the simulated annual surface temperature timeseries is plotted against the simulated total annual energy yield of the rooftop PV installation, grouped by the roofing configuration (colored markers). Each marker of the same color represents one simulation of the same roof type and the markers with orange outline are the roof type baselines (see Table 2). The simulation using 2019 ambient temperature is shown as a red dot.

In line with previous findings, the reflective roof has a consistently lower 95th-quantile surface temperature and higher annual energy yield, compared to the black and gravel roofs. Depending on the design assumptions, the annual energy yield is overestimated by as much as 4%, compared to the gravel roof. Interestingly, the cool roof electricity generation is similar to the generation obtained with the assumption that surface temperature is equal to ambient temperature, suggesting that the standard SAM assumption leads to the best-case scenario for PV panel output, which occurs on a cool roof.

3.4. Sensitivity of surface temperature and energy yield

Overall, the results show that the adapted SAM model developed in this study allows solar energy planners to differentiate between the benefits of different rooftop configurations. Cool roofs outperform green roofs for PV energy yield; however, potential improvements of both systems are non-negligible, even in relatively cooler climate regions like Switzerland. Future, multi-objective analyses of sustainable roof configurations that include the aspect of PV energy are needed to determine which sustainable roofing configurations should be implemented.
properties, the reflective roof 95th-quantile surface temperature could be up to 35 °C cooler than the black roof, which increases annual energy yield by 2.5 MWh. The green roof 95th-quantile surface temperature is slightly hotter than the cool roof, by about 5 °C for the baseline. However, for the same 95th-quantile surface temperature, the energy generation is lower on the green roof. This is due to the fact that temperature and radiation peaks occur in the same hour on a green roof, unlike the cool roof, which reduces panel efficiency when the most solar radiation is available.

These results also highlight the sensitivity of the surface temperature and the annual energy yield within roof types, due to variations between design parameters (i.e., modeling parameters). For a cool roof, the albedo plays the most relevant role in electricity generation. In general, the PV yield is most sensitive to the albedo, the emissivity, the roof view factor (i.e., shading) and the thermal conductivity of the top layer, whereas a majority of the other parameters (e.g., heat capacity, ponding factor, crop coefficient) do not largely influence the yield. A cool roof with an albedo of 0.85 produces the largest energy yield out of all configurations tested (top left corner of Fig. 9). However, without proper maintenance, dust and dirt can collect on the roof, reducing the albedo of a cool roof by up to 0.15 in the first year [71]. A cool roof with a two-year-old, weathered white membrane (albedo of 0.55) leads to the lowest energy yield out of the cool roof scenarios (blue point on the bottom right in Fig. 8). Thus, a poorly maintained cool roof would lead to a similar energy yield as the baseline green roof. On the other hand, a poorly designed green roof can perform worse than a rock ballasted roof. For example, green roofs with low soil thermal conductivity (typical of dry and porous soils [72]), could generate less electricity than a rock ballasted roof with high albedo. It is clear that variations in certain roof parameters can considerably alter the PV yield and thus knowledge of these parameters will improve the accuracy of simulations. The sensitivity analysis of the roof parameters is further discussed in Section A.5 in the Appendix.

The sensitivity analysis also highlights the parameters that would be important to optimize, which is particularly relevant for green roofs [8]. The roof view factor should be reduced, meaning that roof surface (under the panels) should be shaded as much as possible. For a green roof, this can be accomplished by increasing the leaf area index of the vegetation (defined as projected area of leaves over a unit area [73,74]). The larger leaf surface area protects the roof surface from direct solar radiation, which reduces the surface temperature [75]. A green roof with 90% of its surface covered by vegetation (green dot in the upper left part of Fig. 8) has a 95th-quantile surface temperature that is lower than ambient temperature and thus a higher energy output. On the other hand, energy yield is not sensitive to changes in the crop coefficient, indicating that variations in evapotranspiration due to different vegetation properties (e.g., stomatal resistance [8,74]) will not considerably influence roof surface temperature and PV energy yield. It is thus possible to conclude that the leaf area index will be one of the most relevant vegetation parameters due to shading potential, which is consistent with previous findings [14]. Another effective measure to increase the energy yield on green roofs is to use plants with high albedo and apply a thick layer of soil (see Fig. A7 in Appendix), which will reduce the amount of sensible heat released by the green roof.

Finally, when comparing the 95th-quantile roof surface temperatures to the energy yield for all sensitivity scenarios, it is clear that a linear relationship emerges. The linear relationship is somewhat surprising, given that variations in solar radiation can also play a considerable role in PV output. However, since the solar radiation is equivalent across all sensitivity scenarios, this variation is not demonstrated in the figure. Linear regression was thus used to establish a correlation between the 95th-quantile of the annual surface temperature and the annual energy yield, shown as a black line in Fig. 8.

A high inverse correlation ($r^2 = 0.96$) was found, confirming that higher roof surface temperatures will lead to a loss in electricity generation. An increase of one degree Celsius in the 95th-quantile surface temperature leads to a reduction in the energy yield of 71 kWh. Compared to the baseline energy yield of the gravel roof, the annual electricity generated is reduced by approximately 0.17% of for each degree Celsius that the 95th quantile of the roof surface temperature is increased. In comparison, an increase of one degree Celsius in the cell temperature leads to an efficiency loss between 0.4% and 0.5%, depending on the solar panel type. Overall, the strong linear relationship between the 95th-quantile surface temperature and the annual energy yield established in this study could be used to estimate PV-yield in future studies that simulate surface temperature for heat mitigation or building energy saving assessments. This relationship could also be used to estimate losses in PV-yield due to increases in annual surface temperature as a result of climate change, which is expected to bring more extreme heat days [76].

4. Conclusions and future work

This study presented a novel, integrated method to evaluate the energy yield of solar PV panels for different roofing configurations. A rooftop energy balance model was combined with a physically-based solar energy model (the System Advisor Model) to evaluate the improvements in PV energy yield that could be obtained by replacing traditional black membrane or rock ballasted roofs with sustainable, green or reflective (cool) roofs. By accounting for both the roof configuration characteristics and the local climate conditions, this approach broadens the planning instruments that stakeholders can use for rooftop PV installations. The main conclusions of the study are as follows:

- For the case study in Dübendorf (Switzerland), the validation showed that the adapted SAM model, which considers the roof surface temperature, improves the model performance with respect to the standard SAM version, which assumes roof surface temperature is equal to ambient temperature.
- Due to a reduction of peak roof surface temperature in summer, the use of sustainable roofing configurations could improve rooftop PV energy yield by as much as 4% annually in a cooler, temperate climate. Cool roofs are able to generate approximately 2% more electricity than green roofs, on average for the year.
- The PV panel yield is most sensitive to the roof albedo, shading and thickness, demonstrating that optimizing these parameters on sustainable roofs could considerably augment their benefits. For green roofs, the leaf area index (related to shading) is likely to play a more important role than vegetation properties related to evapotranspiration.
- By scaling up results for the studied PV installation (156 solar panels), converting rock ballasted roofs to sustainable configurations could increase national electricity generation in Switzerland by 32 and 60 GWh per year, for green and cool roofs respectively.
- An inverse, linear relationship was found between the energy yield and the 95th-quantile of the roof surface temperature. For every degree that the 95th-quantile of the roof surface temperature is decreased (through the use of sustainable roofs or by altering design parameters), the energy annual yield can be increased by 71 kWh per year. This relationship could be used to estimate the consequences of rising temperatures due to climate change on the energy yield of solar panels.

While this analysis is a first step towards characterizing the influence of sustainable roofing configurations on solar energy yield, there are several limitations that could be improved in future work.

- The rooftop energy balance model used in this analysis is simplified in order to reduce the number of required input parameters; this enables the energy balance model and the SAM model to be more easily integrated by stakeholders. The simplified energy balance model could be improved with more complex models available in the
literature (e.g., [3, 4, 17, 77]) that directly consider additional green roof properties, such as soil moisture content, leaf area index and stomatal resistance. However, the added value of increasing the model complexity and input parameters should be compared to this simplified approach that is easier to adopt and validate.

- This simplified model also does not consider energy feedbacks between the solar panels and the roof, since the surface temperature is solved independently of the PV temperature. Integrating the energy balance model directly into the source code of the SAM model would allow for consideration of these feedbacks, which could be relevant.

- Finally, this model was only tested for limited climate conditions (in Zurich in 2019) and for a single PV installation (156 multicrystalline silicon solar panels). Results may change in other climate regions, in a more extreme and variable future climate, as well, depending on the solar panel type (e.g., bi-facial [78], perovskite), PV panel configuration (e.g., panel tilt, distance from the roof), and installation type (e.g., land based solar farms, agrivoltaics [79], floating PV panels).

The adapted SAM model developed in this study allows green and cool roof choices to be incorporated into solar energy planning. Potential improvements to PV yield due to these sustainable roofing configurations are non-negligible, even in relatively cooler climate regions like Switzerland. Future work should incorporate these findings with other multi-functional benefits of sustainable roofing configurations, including: urban heat mitigation, building energy savings, stormwater attenuation, and biodiversity enhancement. Multi-criteria decision analyses that combine these multiple environmental benefits with economic and social objectives are needed in order to make a holistic decision about the choice of roofing configuration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117082.

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