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Performance assessment method for roof-integrated TSSCs

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Abstract

This paper proposes a performance assessment method for roof-integrated two-stage solar concentrators (TSSCs) as thermo-photovoltaic systems using a parametric modeling approach. The productivity of TSSC systems depends on system design and building geometry. Thus, the proposed approach is intended to be a rigorous yet adaptable method to inform decision-making and promote the use of TSSCs as sustainable energy production systems integrated into buildings. The method allows generating various design alternatives by controlling a set of input parameters for building and TSSCs. We validate the method in an illustrative case study of a single-family house (California). 20,736 design options were generated featuring various combinations of the design parameters. These were evaluated in terms of the annual average load match index (av.LMI), the number of solar cells, and the covered roof area. We further perform a sensitivity analysis to find the relative importance of design parameters and discuss our results in terms of maximizing av.LMI and minimizing number of cells and covered roof area. The method enables designers to adopt a performance-based approach to improve buildings and TSSCs. Hence, the method serves as a foundation for future employing generative design approaches to support informed decision-making processes in early design stages.

Keywords: Two-stage; solar concentrator; energy; roof-integrated; parametric modeling; performance.
Nomenclature

TSSC Two-stage solar concentrator
av.LMI Annual average load match index
CO2 Carbon dioxide
CR Concentration ratio
PV Photovoltaic
DNI Direct normal irradiance
Ee
Eth Thermal energy yield
GR Geometric ratio
SD Separation distance between mirrors
η_{lop} Optical efficiency
τ Transmission coefficients of the mirrors
ρ Reflectivity coefficients of the mirrors
P_{mod,r} Annual average electrical energy production from the solar cell
k_{t} Power thermal coefficient
η_{c} Solar cell efficiency
f Non-idea tracking factor
n_{c} Number of cells per module
η_{mod} Module efficiency
p_{par} Loss factor
η_{inv} Inverter efficiency
A_{sc} Solar cell area
Q_{th,id} Thermal energy ideally delivered by the module
Q_{th,l} Thermal energy dispersion
ε_{c} Cell emissivity
Introduction

Globally, buildings are responsible for over 30% of energy consumption and of large CO2 emissions [1,2]. The integration of solar technologies in buildings is becoming increasingly important to alleviate climate change and reduce greenhouse gases. Concentrating thermo-photovoltaics can potentially address several building energy applications [3]. A concentrating thermo-photovoltaic system mainly consists of mirrors, tracker, and receiver. The mirrors follow the sun path with help of the tracker and focus the incoming sunlight which is absorbed in the receiver [4]. The receiver represents multi-junction solar cell and an active cooling system for electrical and thermal energy production. Based on mirrors, the concentrators can be classified into different geometries [5]. A typical two-stage solar concentrator (TSSC) consisting of primary and secondary mirrors (where the sunlight is reflected from the primary towards the secondary mirror and is absorbed at the receiver) appears to be the most promising design for concentrating thermo-photovoltaics due to efficient power delivery with a high concentration ratio (CR) allowing modular deployment [6,7]. However, TSSCs have attracted less attention compared with one-stage concentrators in buildings as concentrating thermo-photovoltaics [3]. Therefore, it is important to understand which TSSC design performs best on a specific location, which is achievable by mimicking several design parameters.
Energy yield is constrained by the building architecture affecting the surface availability for solar energy harvesting. An ad-hoc solar potential analysis becomes essential throughout different design stages. At an early design stage, such analyses are challenging due to the lack of building geometries that are required to be adjusted to maximize the energy yield. Furthermore, in the integration process, several questions should be addressed e.g., what are the optimal location on buildings or which building design achieves best direct normal irradiance (DNI); and how the various building parts and solar energy system components are combined. This complex decision making process can be supported by developing parametric models that allow exploring various designs and assess their performance quickly [8,9,10,11,12,13]. However, these models were only developed for building-integrated photovoltaics (PV). Additionally, different but often related design concerns regarding installation of concentrating thermo-photovoltaics on buildings are normally treated, in the current practice, in multiple but separated design stages [14,15,16,17,18]. Moreover, these systems are installed once the building design is finalized. This makes seamless integration, one of the major design concerns, far from satisfying. To this end, we propose a method to address related design concerns and to assess the performance of roof-integrated TSSCs as concentrating thermo-photovoltaics through a parametric model featuring the design parameters of both building and TSSCs. The performance of each design alternative is assessed in terms of covered roof area, the number of solar cells, and annual average load match index (av.LMI) in several design scenarios, and iteratively exploring the trade-offs among these indicators. The method helps designing buildings that are energy autarkic. The main working hypothesis is that the performance can be substantially improved based on the parametric modeling approach. We test this hypothesis in an illustrative case study and perform a sensitivity analysis to investigate the relative importance of design parameters.

The paper is structured as follows. Section 2 provides a literature review on concentrating thermo-photovoltaics and the novelty of our approach. Section 3 presents the proposed method highlighting the principal components. Section 4 represents the method implementation in an illustrative case study. In section 5, we present our results followed by the discussion and limitations in section 6. Finally, section 7 concludes the paper.
2 Literature review

There are three aspects related to the use of concentrating thermo-photovoltaics in buildings: (1) design scope, (2) performance, and (3) modeling tools. Traditionally, design scope is divided into separated and subsequent stages, such as system design stage and building architecture design stage. In each stage, design is performed by respective experts with proprietary models regarding specific domain concerns. For instance, an energy engineer designs the energy system, and an architect designs the building. Regarding the system design, one-stage solar concentrators including parabolic dish [15,16,17,18,19,20,21,22] and trough [20,23,24,25], and flat [20,26,27] reflectors are most widely used designs for concentrating thermo-photovoltaics. However, one of the key targets when designing such energy systems is to increase their CR to maximize energy yield and minimize the receiver size, and reduce the number of modules [14,15,16,17,18]. Compared with one-stage designs, TSSCs [6,7] in particular cassegrains (employing parabolic primary and parabolic, hyperbolic, or elliptical secondary mirrors) [5] offer high CRs [28] and have a high potential for concentrating thermo-photovoltaics [26,29,30]. Despite the technical potential, there is little work regarding the use of TSSCs in concentrating thermo-photovoltaic applications in buildings [26,29,30,31]. Another important aspect is the system design flexibility. Studies mainly investigated energy system-related design parameters e.g., optics [14,15,16,17,18,27], system size [23,27], focal distance [19], and CR [14,15,16,17,18] without considering building design parameters. In addition, these studies were limited to one-stage concentrators. In TSSCs, size, design complexity, low compactness, and use of precise trackers [5] are major design challenges, where the lack of system and building design flexibility remains a major drawback in existing methods [26,29,30,31]. The performance of TSSCs can be significantly improved by investigating mirror diameter [32], the geometric ratio [7], separation distance [7,32], and mirrors’ shape [33]. However, there is still a lack of full performance characterization of TSSCs in particular for concentrating thermo-photovoltaics. This can be supported by manipulating different system and building related design parameters and assessing performance in multiple scenarios through parametric design as suggested in [5].
Regarding the building architectural design stage, evaluation of DNI on fixed flat roofs followed by a pre-designed, concentrating thermo-photovoltaic system integration is a common practice [14,15,16,17,18]. Hence the integration mostly remains as a separate step that follows once the building design is fixed [14,15,16,17,18]. However, these divide-and-conquer approaches to design the energy system and the building separately are only effective when domain concerns are orthogonal towards each other. Yet, the concerns related to the design of the energy system and the building are often related. Our vision is that buildings can be purposefully designed to maximize the energy yield.

For instance, the roof has a significant impact on solar access and its design can be manipulated to control it [9,11,34,35,36,37]. The main parameters that can be used to determine solar access are roof shape [10,11,38,39,40,41,42,43], slope [12,39,44,34,43] and orientation [10,41,43,44,45,46]. The majority of studies performed solar access analysis on the tilted roof, among which shed, gable, and saltbox are widely studied [34,38,43]. However, these studies are limited to flat-plate PV. Moreover, in literature most work related to concentrating thermo-photovoltaics is limited to existing buildings [14,15,16,17,18]. This is of course a step forward towards converting the existing building assets into active energy producers. For the new buildings, a perfect integration between energy system and building can be realized from the design phase by assessing various building designs to achieve the best DNI. This can be achieved by generating and evaluating several roof designs by using parametric models featuring control design parameters such as roof shape, slope, and orientation [34,41,43]. Thus, the optimal integration of concentrating thermo-photovoltaics demands that building architecture and energy system, in particular TSSC, should be designed and assessed at the same time, collaboratively rather than separately.

Regarding the design performance, av.LMI is an important energy performance metric capturing the balance between the yield and demand it reflects the energy demand fulfilled by the system [47]. Studies investigated the impact of urban forms on LMI that are limited to flat-plate PV [43,47]. Moreover, the number of modules covering the roof and solar cells are two important indicators to represent the cost-effectiveness of an energy system. Studies adopted modular configurations of roof-installed concentrating thermo-photovoltaics according to energy demand [14,15,16,17,18] and...
investigated modules’ size and the number of solar cells. However, these studies are limited to existing buildings with a fixed roof shape (flat) and use of one-stage concentrator. To achieve good integration of concentrating thermo-photovoltaics with buildings, several coupled concerns should be addressed in the initial design stage. The performance concerns considered in this study as a good measure of a building-integrated energy system are related to architecture (i.e., the area covered by modules), energy (i.e., av.LMI), and cost (i.e., the number of solar cells).

Regarding the modeling approaches, previous studies employed various tools to simulate various aspects. The focus is mainly on using commercial software such as TRNSYS [23,48,49], and MATLAB [15,16,17,21,50] for performing analytical modeling, or combined several tools [20,22,51,52]. However, these studies used the built-in component library available with tools which do not allow for a certain level of building architecture and system design flexibility. The majority of these studies mainly investigated energy system-related design inputs considering fixed building geometries. In the current literature, there exists a lack of methods specifically addressing the concurrent design of building and concentrating thermo-photovoltaic using TSSCs [14,15,16,17,18], combining several simulators into single modeling platform for studying interdependencies among solar potential in terms of DNI on buildings, energy system size and performance across several domains by utilizing and integrating the advanced parametric modeling techniques. There exist a limited number of research studies [8,9,10,11,12,13] on developing hypothetical parametric models with a common goal to make the performance-based building design more accessible in the early design phase. For example, studies investigated the impact of building designs on solar accessibility and energy yield [47]. However, all this work is limited to the integration process of flat-plate PV with building geometry. Current literature shows that none of modeling approaches allow simultaneous assessment of multi-disciplinary performance e.g., solar irradiance, energy yield, energy system size, and cost. Additionally, the parametric models proposed in existing literature [8,9,10,11,12,13] only focused on building geometry and failed to exploit the full potential of discipline-integrative systems view. These approaches are limited to the parametric design of building geometry, and none of these focused on creating design alternatives of building-integrated solar technologies, in particular, concentrating thermo-photovoltaics.
The research gaps identified in the current literature and which represent the focus of this study are:

(1) the lack of integral, and correlative design of concentrating thermo-photovoltaics and building architecture, (2) the lack of explorative designs based on parametric models combining energy system and building related design parameters, and (3) very little focus on the use of TSSCs as concentrating thermo-photovoltaics as building-integrated energy systems. As a result, this study develops a performance-driven method exploiting a systems engineering approach that enables designers to make parametric changes to the roof and TSSC for the concentrating thermo-photovoltaic application, run solar irradiance analysis, and simulate the performance. The method is novel in that the parametric design enables simultaneous design of both building and TSSC, and allows flexibility concerning the TSSC and roof design in an early design stage. Our method aims to investigate av.LMI, number of solar cells, and covered roof area by modules according to energy demand and available DNI on the roof [14,15,16,17,18,47]. Hence, we achieve a perfect integration by bringing together all issues in terms of architectural, energy, and cost aspects. The parametric runs enable generative design and assess the performance to search for the most efficient design options. This leads to out-of-the-box solutions to complex design problems that require meeting multiple challenges simultaneously. The parametric design features various combinations of roof shape [38,40,43] and slope [34,43], orientation [53], TSSC type [5], geometric ratio [7], and separation distance [7,32]. We also investigate the significance of the impact of design parameters on performance indicators through sensitivity analysis. The following section described the proposed method.

3 Proposed performance assessment method

The proposed performance-driven method is structured in five successive steps (Fig. 2). The first step is geometry generation step that requires the creation of the parametric model of roofs and TSSCs designs considering several design parameters for controlling their geometry. The second step is a simulation step that performs the solar irradiance assessment on the roof generated at step 1. The third step is an assessment step that evaluates the energy performance evaluation of TSSCs in the context given by the roof generated at step 1.
The fourth step is the integration step that integrates and distributes the required numbers of TSSCs on the roof. Finally, the fifth step is an assessment step that assesses the integrated design performance in terms of av.LMI, covered roof area, and the number of solar cells. The following sections describe each step in detail.

### 3.1 Parametric model

In the first step, we assume design constraints (fixed), and design parameters (variable) based on the pre-defined ranges (Table 1). We also consider energy demand and weather conditions as environmental constraints.
Table 1 Design parameters which we tested with the proposed method.

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof type</td>
<td>Shed, Gable, Saltbox</td>
</tr>
<tr>
<td>Roof slopes</td>
<td>$5^\circ - 30^\circ$</td>
</tr>
<tr>
<td>Building orientation</td>
<td>$0^\circ - 315^\circ$</td>
</tr>
<tr>
<td>TSSC type</td>
<td>cass-I, cass-II, cass-III, cass-IV</td>
</tr>
<tr>
<td>Geometric ratio</td>
<td>1379 – 1807</td>
</tr>
<tr>
<td>Separation distance</td>
<td>0.35m – 0.71m</td>
</tr>
</tbody>
</table>

Fig. 2 Roof designs investigated in the method, where W represents the width, H represents the height, L represents the length, and N represents the North direction.

The roof design is generated based on the following parameters: roof type and slope [34,43], and orientation [53] with building dimensions as design constraints. The scope of this study is limited to shed, gable, and saltbox roof types [34,35,38,43,53] (Fig. 2).
Additionally, the TSSC design is generated based on the following parameters: TSSC type [5], geometric ratio (area ratio between aperture and solar cell) [7,28], and mirrors’ separation distance [7,32] (Fig. 3), and design constraints: mirrors, and cell properties, module and inverter efficiency, and tracking factor [16]. Due to their potential for concentrating thermo-photovoltaic applications [26,29,30], we investigate the cassegrain type of TSSCs. There are several cassegrain designs based on the shapes of mirrors as classified in [5]. However, we investigate four types as: (1) a parabolic primary and a parabolic secondary mirror (‘cass-I’), (2) a parabolic primary and a hyperbolic secondary mirror (‘cass-II’), (3) a parabolic primary and a prolate (long) elliptical secondary mirror (‘cass-III’), and (4) a parabolic primary and an oblate (wide) elliptical secondary mirror (‘cass-IV’). After defining parametric relations and creating roof and TSSC designs, the next step is to assess the DNI on roof as discussed.
in the following section.

3.2 Solar irradiance assessment

Account for weather conditions as environmental constraints, at this step we use a weather data file (.WEA) that contains hourly data of the cumulative radiation about a particular geographic location over a particular period. The irradiance assessment through simulations uses this data to figure out how much insolation falls on the selected roof surfaces due to shading, time range, and surface angles. The aim is to obtain the DNI on the roof design generated at step 1 (before integration of TSSCs). The available DNI will have a direct impact on final energy generation from the TSSCs. The method allows estimating hourly, daily, to annually-averaged DNIs. However, the focus of this study is to design a system for annual average energy demand, therefore, we assess an annual average DNI on each roof design. The resulting DNI values are used to perform energy simulation as discussed in the next section.

3.3 Energy performance evaluation

The primary objective of this step is to design an energy system to satisfy the electrical and thermal energy demand. Before integration, we optically simulate TSSCs to estimate the CR using a ray-tracing principle under the recorded DNI for the roof design. The CR represents the maximum energy gain from a TSSC defined as the ratio of the irradiance on the receive ($I_r$) to the DNI at the entrance aperture [54] and is given below:

$$ CR = \frac{I_r}{DNI} \quad (1) $$

The estimated CR helps to calculate the optical efficiency ($\eta_{op}$) using the mathematical formulation as shown in Eq. (2) [16]:

$$ \eta_{op} = \tau.\left[p + \frac{1}{CR}.(1 - \frac{\rho}{0.98})\right] \quad (2) $$
where \( \tau \) and \( \rho \) represent the transmission and reflectivity coefficients of the mirrors. The mirrors reflect the radiation on triple-junction cells InGaP/InGaAs/Ge (indium–gallium–phosphide/indium–gallium–arsenide/germanium) placed at the bottom of the TSSC. This study uses a similar approach to calculate energy yield and investigate the number of solar concentrators and solar cells as in [14,15,16,17,18]. However, these studies were limited to modeling a one-stage concentrator (parabolic dish), installed on a flat roof, with fixed mirror dimensions, and authors only varied cell dimensions and CRs. We inspired our approach from these studies and custom tailored it to fit our needs. Hence, we focus on TSSC geometries and vary a wide range of building and TSSC design parameters (Table 1). We evaluate the annual average electrical energy production from the solar cell \( P_{mod,r} \) as [16]:

\[
P_{mod,r} = ((k_t \cdot \eta_c \cdot \eta_{op} \cdot f \cdot \eta_{mod}) - p_{par}) \cdot \eta_{inv} \cdot CR \cdot DNI \cdot A_{sc} \cdot n_c
\]

(3)

Where \( k_t \) is the power thermal coefficient, \( \eta_c \) is the cell efficiency, \( \eta_{op} \) is the optical efficiency, \( f \) is the non-idea tracking factor, \( n_c \) is the cells per module, \( \eta_{mod} \) is the module efficiency, \( p_{par} \) is a loss factor, \( \eta_{inv} \) is the inverter efficiency, and \( A_{sc} \) is the solar cell area. Based on energy generation (Eq. 3), we calculate the number of required TSSC modules (ratio of energy demand to energy produced from one module). We estimate a total number of modules to fulfill an annual average energy demand. The solar cell is placed on a plate where the cooling fluid flows in pipes and the thermal energy ideally delivered by the module is equal to [16]:

\[
Q_{th,id} = (1 - \eta_c \cdot \eta_{mod} \cdot k_t) \cdot \eta_{op} \cdot CR \cdot (DNI \cdot f) \cdot A_{sc} \cdot n_c
\]

(4)

Moreover, the concentrated sunlight on the cell determines its heating and thermal energy dispersion because of radiative and convective phenomena [16]:

\[
Q_{th,l} = [\bar{h}_c \cdot (T_c - T_o) + \epsilon_c \cdot \sigma \cdot (T_c^4 - T_o^4)] \cdot A_{sc} \cdot n_c
\]

(5)

where \( \epsilon_c \) is the cell emissivity and \( \bar{h}_c \) represents the system working hours (e.g., DNI
Finally, the real thermal energy ($Q_{th,r}$) is equal to [16]:

$$Q_{th,r} = Q_{th,ld} - Q_{th,l}$$  

From an annual energy generation (electrical and thermal), we calculate the av.LMI reflecting the temporal coverage ratio of energy consumption by total energy generation [47,55] and is equal to (Eq. 7).

$$\text{av. LMI} = \frac{1}{N} \sum_{year} \min \left[ 1, \frac{N_{\text{mod}} \cdot g_i(t)}{l_i(t)} \right]$$  

Where $N_{\text{mod}}$ is the number of required modules, $g$ is the energy generation from a single module, $l$ is the energy load, $i$ is the energy carrier, $t$ is the time interval (hour, day, or month), $N$ is the number of data samples (e.g., 12 for a monthly time interval). With required number, finally the TSSC modules are integrated with the roof as discussed in the following section.

### 3.4 Design integration

In this step, we calculate the required number of modules according to the site, available DNI, energy demand, and design configurations of both TSSCs and roof. Energy simulations allow estimating a total number of modules and respective solar cells (we assume one cell per module). We calculate the area occupied by the modules including module diameter and the separation distance between adjacent modules. The integration process involves calculating the distribution of TSSCs on the roof in terms of parallel rows and modules per row and estimating the covered roof area by modules and the required number of solar cells. The covered roof area represents the percent of the roof area occupied by modules relative to the total roof area.

### 3.5 Design assessment

This step allows the user to assess the performance of each design generated by updating the building and TSSC design parameters according to a pre-defined range and moving through the above
process described by steps 1 to 4. As indicated in previous sections, the performance indicators we consider are av.LMI, covered roof area, and the number of solar cells. The proposed performance-driven method allows the generation of a large number of design options automating the process that is required to be performed on a design from input to performance assessment. The breadth of design alternatives is given by the possibility to combine different possible values for the input parameters. Needless to say, that even considering the automated process laid down by the proposed method, the variation of parameters and exploration of all possible scenarios is still time consuming. Yet, some of the input parameters might not have significant impact on the performance metrics. To this end, we also perform a sensitivity analysis to compare the relative importance of design parameters that contribute the most to the variability of the performance. We validate the method in an illustrative case study as discussed in the following section.

4 Validation approach

To validate the method, we conducted a parametric study analysing the possibility to install TSSCs on a single-family detached house (size 186 m$^2$ – 232 m$^2$) in California. We chose this example because single-family detached dwellings are the most common types of residential buildings in California [56].

Table 2 Design and environmental constrains in the proposed method.

<table>
<thead>
<tr>
<th>Environmental constraints</th>
<th>Value</th>
<th>Design constraints</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location:</td>
<td></td>
<td>Building:</td>
<td></td>
</tr>
<tr>
<td>Latitudelatitude</td>
<td>33.61</td>
<td>Length (L)</td>
<td>13 m</td>
</tr>
<tr>
<td>Longitude</td>
<td>-114.58</td>
<td>Width (W)</td>
<td>16 m</td>
</tr>
<tr>
<td>Energy demand:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space heating</td>
<td>8564.288 kWh</td>
<td>Height (H)</td>
<td>10 m</td>
</tr>
<tr>
<td>Water heating</td>
<td>5044.712 kWh</td>
<td>Floor area</td>
<td>208 m$^2$</td>
</tr>
<tr>
<td>Air-conditioning</td>
<td>1935.761 kWh</td>
<td>System: Tracking factor ($f$)</td>
<td>0.9</td>
</tr>
<tr>
<td>Total annual</td>
<td>15,545 kWh</td>
<td>module efficiency ($\eta_{mod}$)</td>
<td>0.9</td>
</tr>
<tr>
<td>(electrical)</td>
<td></td>
<td>loss factor ($p_{par}$)</td>
<td>0.023</td>
</tr>
<tr>
<td>Refrigerators</td>
<td>909.221 kWh</td>
<td>inverter efficiency ($\eta_{inv}$)</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Moreover, the integration of solar technologies with buildings has a huge potential in California. We considered annual average electrical and thermal energy consumption (Table 2) [57]. We explore several designs (Table 1) considering environmental and design constraints (Table 2). We used an hourly data of the cumulative radiation (in .WEA file) for the location of California (Table 2) over a year. We implemented the proposed performance-driven method (Fig. 4) using Dynamo [58], SolTrace [59], and R [60]. Dynamo is an open-source visual programming application. Dynamo allows for manipulating data, exploring different designs, automating processes, manipulating, and interconnecting complex systems, and other simulation engines. We use Dynamo’s code blocks, a text-scripting interface for all calculations. SolTrace is an optical ray-tracing software for solar concentrators. The scripting functionality of SolTrace, LK allows optical simulation and data exchange between SolTrace and other tools.

<table>
<thead>
<tr>
<th>Others</th>
<th>6657.847 kWh</th>
<th>cell size ($A_c$)</th>
<th>81 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual (thermal)</td>
<td>7567 kWh</td>
<td>cell emissivity ($\epsilon_c$)</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Fig. 4 The workflow of proposed method implementation.

R is a free and well-known programming language for statistical computing and graphics. The
implementation begins with developing the parametric model and irradiance analysis on the roof in Dynamo. The analysis for this study is performed over the period of one year (01-01-2020 – 31-12-2020) with climate data for the location of California. We import the annual average DNI and TSSCs' design inputs into SolTrace to optically simulate TSSCs. Then, we import the optical analysis results (CR) from SolTrace in Dynamo and calculate the optical efficiency, the number of modules, annual average electrical and thermal energy generation, av.LMI, number of solar cells, and covered roof area (Eq. 2 – Eq. 7). Finally, we integrate the TSSCs with the roof by defining the distribution of modules in terms of parallel rows (ratio of roof area to module area) and modules per row (ratio of required modules to total rows) in Dynamo. With a distance of 10 cm between modules in a row, we also calculate the covered roof by modules. We generate several design options featuring different combinations of design parameters. To find the interesting patterns between design parameters and performance indicators, we use parallel coordinate graphs [61,62] using R, where the parameters are represented with their own vertical axis and are evenly spaced and parallel located. The values are represented as a series of lines across the different axes. We further perform a local sensitivity analysis to investigate the effect of a design parameter by keeping other parameters to baseline settings [63]. We describe the baseline case by considering the shed roof (slope of 15°, orientation of 180°), and cass-l type of TSSC (geometric ratio of 1460, separation distance of 0.47 m). We represent corresponding results in R as discussed in the following section.

5 Results

The relevant results for different scenarios in design exploration are discussed in section 5.1 along with the significance of the effects of design parameters on performance through sensitivity analysis in section 5.2.

5.1 Design exploration

Fig. 5 illustrates the main results of our parametric study using parallel coordinate plots where each line represents a design space and performance across different indicators.
In Fig. 5, we represent three cases, baseline, worst, and optimal designs. Results of baseline case show that annual average DNI of 2237 kWh is achievable with some shading on the shed roof. However, we require 495 cells used in cass-I type modules that cover ≈24% of the roof, offering an av.LMI of 1.88 (Fig. 6a).
The worst design combines a gable roof (slope=30\(^\circ\), orientation=180\(^\circ\)), and cass-III (separation distance=0.71 m, geometric ratio=1550). The solar analysis shows an annual average DNI of 1751
kWh with most part of roof still getting less irradiance (Fig. 6b). In the worst case, with average CR (<1000), we need a large number of cells (671) with cass-III modules to meet 100% electrical demand. However, with excess thermal yield, av.LMI is still above 1.0 (≈ 1.8). With 24 rows (28 modules per row), these modules cover 33.8% of the roof (Fig. 6b). The optimal designs match certain performance threshold e.g., low covered roof area (<20%), high av.LMI (>1), and lesser cells (<400). These designs show low pitched roofs with a high DNI (>2200 kWh) including shed roof (slope=10°, orientation=0°) (Fig. 6c), gable roof (slope=5°, orientation=315°) (Fig. 6d), gable roof (slope=10°, orientation=45°) (Fig. 6e), and saltbox (slope=15°, orientation=315° (Fig. 6f). Although we still observe some shading on roof, but the shed roof achieves better irradiance distribution among all. With a higher DNI, optimal roof designs show better energy yield and av.LMI (≥ 1.9) and support a certain TSSC geometry. For example, on shed roof (Fig. 6c), cass-IV modules (geometric ratio=1629, separation distance=0.47 m) achieve high CR (>1500), allow only 250 cells, and with 10 parallel rows (25 modules per row) modules cover 13.3% of the roof. Similarly, on a gable roof (Fig. 6d), cass-II modules (geometric ratio=1461, and separation distance=0.547 m), allow 245 cells, and with 9 parallel rows, 28 modules per row, cover 11.7% of the roof. While cass-III modules (geometric ratio of 1629 and separation distance of 0.56 m) on gable (Fig. 6e) use 266 cells and with 10 parallel rows, 27 modules per row, cover 14.1% of roof. While a saltbox roof supports cass-I design (separation distance=0.4 m, geometric ratio=1379) allowing 355 cells, and with 13 parallel rows (28 modules per row) these modules cover 16% of the roof (Fig. 6f). Optimal designs ensure a low covered roof with lesser modules and solar cells leading towards cost-effective solutions, and a high av.LMI increasing the energy reliability. Results show that it is possible to modify system layout on the roof e.g., rows and number of TSSCs per row in different ways according to roof and TSSC designs unlike in [14,15,16,17,18] where number and layout of concentrators was defined based on CR or cell type. Results also show that the distance between TSSC modules depends on certain roof and TSSC design. However, a lower distance can cause shading on modules and performance degradation that can be improved by a high CR and a good DNI. Results also show that a high CR helps to reduce solar cell size and thermal yield, but a solar cell may exhibit efficiency degradation at high CR. We also present the results of sensitivity analysis in the
5.2 Sensitivity Analysis

Fig. 7 shows the impact of design parameters on the covered roof area. The covered roof area is highly sensitive to variation in separation distance, and with a high distance, this area increases to about 100%. While with a smaller distance, covered roof area is 25% less than the baseline case (Fig. 6a). Among all designs, impact of separation distance is less significant in cass-IV. Similarly, geometric ratio has moderate impact on covered roof mainly for cass-II and -III designs. Evidently, the impact of design parameters is strongly influenced by TSSC design.

![Tornado plot showing the percent variation in the covered roof area (%) with variation of design parameters from the baseline case.](image)

The building design parameters have moderate impact on covered roof especially in gable and saltbox roofs. However, the impact of orientation and roof slope varies among roof types. A high slope on gable roof is more influential on increasing the covered roof area, while its impact is minimal on the shed roof. In contrast, with minimal impact, high and low orientation can reduce the covered roof area of up to 25% especially on gable roof. In general, TSSC type, separation distance, and roof slope are the critical parameters when a low covered roof area is required. We further investigate the impact of
parameters on number of solar cells (Fig. 8). Results show that the number of cells is more sensitive to the separation distance than other parameters, where a larger distance can lead to ≈100% increase in the cells. While a lower distance leads to ≈25% of reduction in cells. However, the separation distance has minimal impact on cells in case-IV design. Varying geometric ratio moderately influences the cell numbers. Except for cass-III, high geometric ratio is good for cells reduction (≈20%) but lower ratio is less significant. While in cass-III, lower and upper bounds of this ratio can significantly reduce the cells (up to 40%). However, there is negligible impact of low geometric ratio on cells in cass-II. Moreover, building parameters have moderate impact on the cell.

![Tornado plot showing the percent variation in the number of solar cells (%) with variation of design parameters from the baseline case.](image)

High slope is not recommended when less cells are required which is more significant in gable roof. In contrast, low or high orientation is good to use lesser cells which is more significant on gable roof. While the impact of roof slope and orientation on the cells is less significant in shed roof. Our results highlight that the number of cells is strongly influenced by TSSC type, separation distance, and roof slope. Moreover, impact of design parameters depends on certain roof or TSSC type. We also evaluate the impact of design parameters on av.LMI (Fig. 9). Our results indicate that there is no
significant variation on av.LMI within lower or upper bounds of design parameters. Compared with TSSC, the building design parameters have less impact on av.LMI. Despite this, variation in gable roof orientation can still lead to an increase in av.LMI. Moreover, separation distance has strong impact on av.LMI in cass-II and -III design, moderate in cass-I, and low in cass-IV design. Also, a small separation distance helps improving av.LMI $\approx 1.5\%$, which is more significant in cass-III design.

![Tornado plot showing the percent variation in the average annual load match index (av.LMI) (%) with variation of design parameters from the baseline case.](image)

While a high distance can reduce the av.LMI (up to 2.5%) mainly in cass-II design and is insignificant in other designs. The impact of geometric ratio on av.LMI is more significant in cass-III design with lower and upper bounds lead to a slight improvement in av.LMI ($\approx 1.8\%$) compared with baseline case. However, for other designs, only high geometric ratio helps increasing the av.LMI. Moreover, variation of geometric ratio is less influential to the av.LMI in cass-II design. Evidently, for our case building, compared with TSSC, the building design parameters have a lower impact on av.LMI. Despite their smaller contribution, building designs can still help improving these performance indicators. Our method serves as a basis for integrated and concurrent design of both building and...
TSSCs to support an informed decision-making process in an early design stage. However, there are a few challenges that should be addressed in future studies, as discussed in the following section.

6 Discussion

As the previous exemplary application shows the proposed method offers an opportunity for system modeling of roof-integrated TSSC designs as concentrating thermo-photovoltaic systems for domestic energy applications. Our method allows to design building architecture and TSSC designs simultaneously, and at the same time, leading to a seamless integration of TSSCs with buildings, close to satisfying. The proposed method enables parametric variation in the roof and TSSC design, perform solar irradiance and TSSC’ performance analyses, and suggests calculating av.LMI, covered roof area, and number of solar cells as key performance indicators. We demonstrated the method on a case study of a single-family house (California). To understand how the design parameters of building and TSSCs affect the performance indicators, we explored a wide range of design options featuring various combinations of roof shape [38,40,43] and slope [34,43], orientation [53], TSSC type [5], geometric ratio [7], and separation distance [7,32]. We investigated the performance of designs according to energy demand and available DNI on the roof [14,15,16,17,18,47]. We also investigated the significance of the impact of design parameters of buildings and TSSCs on performance through sensitivity analysis. Our design exploration and sensitivity analysis allow us to assess design space that ensures a good performance in terms of high av.LMI, low covered roof, and less solar cells. We show how the application of the method enables a correlative, integrative, and explorative design of roof-integrated TSSCs. Our method promotes a performative starting point achieved by both building designers and energy analysts. The interconnection of parametric design with irradiance analysis and TSSCs’ performance simulations provides unique opportunities to compare the performance of different designs. This can be useful for building planners and energy specialists to accurately model and identify optimal building and TSSC designs. It can also be relevant for manufacturing companies to assess the performance of different modular TSSC designs in terms of dimension, layout, and solar cell numbers. Our method allows us to achieve a perfect integration by designing building and TSSC...
geometries at the same time and bringing architectural, energy, and cost aspects together. The parametrization enables the generation of designs and the assessment of their performance in several domains to search for the most efficient designs leading to out-of-the-box solutions to complex design problems that require addressing multiple issues simultaneously.

However, there are several limitations of the proposed method, which can be addressed in future research. For example, we ignored several environmental aspects that influence the TSSC performance e.g., humidity, environmental pollutants, temperature, or thermal stress [5]. We did not assess the performance of TSSCs under varying DNIs at different locations that reduced the number and variety of test conditions. Our validation is limited to the case building at the specified location, which might be different for other locations, or building types. Therefore, the method should be tested at different geographical locations and for other buildings by changing both building design and environmental parameters in the existing method. Moreover, we tested TSSCs on an annually averaged DNI, therefore, simulating TSSCs under DNI for other time intervals (e.g., days or months) by employing efficient trackers [64] should be considered in future. The method only takes shed, gable, and saltbox roof types and cassegrain type of TSSC into account which can be extended to many different roof designs e.g., butterfly, mansard, pyramid, or gambrel [65] and to other TSSC designs e.g., two-stage dishes, or two-stage troughs as detailed in [5]. Additionally, some drawbacks related to the typological method remain. We did not include the possibilities of complex building geometries, where urban designers may introduce more complicated building designs in the long run. Furthermore, our sensitivity analysis is limited to the baseline case settings, however, the method should be tested for different baseline simulation parameters and in other climatic contexts. The scope of our method is limited to designing new buildings, which can be extended towards integrating TSSCs with the existing buildings. Moreover, we did not perform shadow analysis due to neighboring buildings, though buildings are usually built in congested urban areas, leading to undesired shadows on the roofs. Hence, the availability of shadow-free installation areas is a major challenge for TSSCs installation in these areas [5]. We also ignored the shadow effects on TSSC modules connected side-by-side. In future research, shadows from surrounding buildings or adjacent modules can be simulated over time.
Moreover, we designed TSSCs of very high CR, that increases the system cost and manufacturing complexity requiring precise tracker. Therefore, future research should be focused on cost-effective solutions e.g., optimal optical designs. We only focused on investigating the electrical and thermal energy yield and ignored other aspects e.g., estimating system and maintenance (e.g., cleaning) cost, sizing storage device, investigating cooling strategy, and modeling protective glazing on top of the modules required to keep the modules clean. Moreover, we implemented the method in an illustrative case study using Dynamo, SolTrace, and R as extensively validated tools however, we did not use the method for a previously reported experimental or simulated study to compare the calculated results with reported results. We did not include a validation part in which the simulation results are verified or calibrated with measured data. For future research, more experimentation is needed, and validations of performance indicators as exemplified in this study should be conducted to gain more valuable insights for real case buildings. Furthermore, we aggregated the energy demand and yield when calculating av.LMI but in reality, there is a difference between the temporal distributions of energy demand and yield from concentrating thermo-photovoltaics. Such a difference requires either an exchange with the energy grid or storage device. This should be addressed in future research. Moreover, we did not introduce the stochastic effects to the method e.g., dynamic demand patterns along with stochastic variation in weather data. We tested the method assuming deterministic environmental conditions, therefore, in future research, stochastic modelling techniques should also be included in the method.

Another major issue is the high computation time when testing a large design space in design exploration. To validate the method, we manually apply a filter to find design space that matches our set performance criteria. As extensions to this method, still, more systematic, and iterative problem formulation is possible that can assure the most efficient definition and exploration. Future work can improve the efficiency of generating designs and deriving analytical input models for different analyses. The design space can be more efficiently generated and explored using optimization methods to extend the analysis scope. Moreover, future work can include finding optimal solutions by applying multi-objective optimization techniques e.g., genetic algorithms. The method should be extended to
integrate other aspects such as cost-benefit analysis, as well as quantification of their environmental benefits to strengthening the role of TSSCs for energy applications. This will provide a way to cost-effective, and environmental-friendly building-integrated TSSC technologies.

7 Conclusions

This research proposes a performance assessment method for TSSCs as roof-integrated concentrating thermo-photovoltaics by applying parametric modeling approach. We validated the method in an illustrative case study of a single-family house. We demonstrated several design scenarios for three roof types as the shed, gable, and saltbox and four TSSC designs as cass-I, cass-II, cass-III, and cass-IV. We explored these design options for different roof slopes, orientations, geometric ratio and separation distance. Our method involves: parametric model development; solar irradiance assessment; energy performance evaluation; design integration; and design assessment. The method calculates av.LMI, covered roof area, and number of solar cells as key performance indicators. The sensitivity analysis indicates that for this case building, TSSC design parameters have more impact on performance compared with building design parameters. Moreover, the analysis indicates that despite their smaller impact, building designs can still help improving TSSCs’ performance. Results suggest that setting a large separation distance, geometric ratio, or slope increase the covered roof area significantly, while low separation distance further helps improving av.LMI in most cases. Moreover, higher separation distance and roof slope leads to a greater number of solar cells. Our method allows us to modify both building and TSSC designs, and test different design scenarios to improve the performance indicators that can be used to meaningfully support the decision making process.

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11. L. Walker, J. Hofer, A. Schlueter, High-resolution, parametric BIPV and electrical systems


