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Review article

Solar energy in the city: Data-driven review on urban photovoltaics

J. McCarty [a,b,*], C. Waibel [a,b], S.W. Leow [c], A. Schlueter [a,b]

[a] Chair of Architecture and Building Systems, ETH Zurich, Stefano-Franscini-Platz 1, Zurich, 8093, Switzerland
[b] Future Cities Lab Global, Stefano-Franscini-Platz 1, Zurich, 8093, Switzerland
[c] Solar Energy Research Institute of Singapore, National University of Singapore, S117574, Singapore

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ABSTRACT

Electrification, achieved through the rapid and widespread deployment of renewable technologies is a pivotal strategy for mitigating climate change over the coming decades. The prevailing expectation hinges on the replacement of existing fossil fuel-based electricity generators with renewable technologies such as photovoltaics. Major challenges arising in the transition towards photovoltaic deployment are their spatio-temporal intermittency as well as their relatively low power density, resulting in a higher land use as compared to centralised fossil fuel-based generators. In response, the generation of energy should be strategically situated alongside areas of demand. These demand hubs primarily manifest in urban settings which produce a separate set of boundary conditions and constraints from typical ground-mount photovoltaic. This calls for a new domain of expertise in the planning and design for PV in urban areas. This research examines the emerging field of “urban photovoltaics” and focuses on the predominance of literature related to building-based photovoltaics. To deepen the comprehension of this dynamic landscape, an extensive body of literature was first organised into ten concise topics using natural language processing. Within each of the topics, focused reviews of select literature were conducted to provide a broad description of research in the urban photovoltaic field. Alongside this analysis, existing research gaps were identified and six research agendas were discerned through a manual distillation of the topics: the need for multi-scalar research, simulation frameworks for partial shading, inclusion of life-cycle assessment, focus on contextual solutions, and understanding of heat in photovoltaic systems and its impact on urban heat island.

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* Corresponding author at: Chair of Architecture and Building Systems, ETH Zurich, Stefano-Franscini-Platz 1, Zurich, 8093, Switzerland.
E-mail address: mccarty@arch.ethz.ch (J. McCarty).

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1. Introduction

The deployment of a diverse range of renewable energy technologies in the near term is essential to meeting rising electrical energy demand while simultaneously mitigating planet-warming greenhouse gases and improving the energy sovereignty of individual nation-states [1–3]. A drawback of rapid renewable deployment is the need for large tracts of land for power generators such as photovoltaic (PV) arrays and wind turbines, as the power density of renewable energy (10^{-1}to10^{1} $W_e m^{-2}$) is much lower than that of steam-driven electricity plants (10^{3}to10^{4} $W_e m^{-2}$) [4,5]. Striving for a no impact policy for anthropogenic energy generation activities on sensitive land is key to enabling ecological stability [6]. Therefore, the co-location of energy generation and demand is often proposed as an ideal solution for present and future energy needs [7].

As the majority of global energy demand and carbon emissions can be attributed to consumption in and for urban populations, small scale distributed energy resources within cities are becoming increasingly common. Distributed energy resources include renewable energy technologies such as PV, but also battery energy storage systems or virtual assets enabled by metering systems and controllers. PV devices that are used in urban areas, termed here as urban photovoltaics (UPV), can be attached to and integrated with urban surfaces (e.g. building facades) to provide on-site generation and additional benefits such as passive shading control for a building [8]. However, while the use of ground mounted PV (GPV) is commonplace in the energy sector, UPV is a nascent market and technology-development space. This has led to the use of research aimed at questions surrounding GPV modelling, performance, and deployment in UPV contexts. While practical, the environmental conditions, regulations, and aesthetic requirements of cities present different circumstances from those found near the sites of GPV.

Abbreviations

Acronym	Meaning	Acronym	Meaning
PV	Photovoltaic	DSSC	Dye-sensitized solar cells
UPV	Urban photovoltaic	OSC	Organic solar cells
GPV	Ground mounted photovoltaic	PSC	Perovskite solar cells
NLP	Natural language processing	BIPV/T	Building integrated photovoltaic thermal
LDA	Latent Dirichlet Allocation	UHI	Urban Heat Island
BoW	Bag-of-words	PCM	Phase Change Material
LLM	Large-Language Model	TAS	Topic association score
BIPV	Building integrated photovoltaic	LCIA	Life cycle impact analysis
GHG	Greenhouse gas	LCA	Life-cycle assessment
a-Si	Amorphous silicon	a-Si:H	Hydrogenated amorphous silicon
LSCs	Luminescent solar concentrators	KPIs	Key performance indicators
LiDAR	Light Detection and Ranging	GIS	Geographic Information System
IV	Current-Voltage		

In Section 1.1, details on the novelty and contribution of this review are provided. In Section 2, we briefly describe the data-driven approach to organise and analyse a large collection of literature related to modelling, deployment, and monitoring of PV in cities and on buildings. Then, from Sections 3.1 to 3.11 the primary literature from each topic is reviewed to provide an understanding of what has been discussed across the field and points to where topical gaps may exist. For each topic reviewed the contents of the primary literature are described and summarised, where the content of the topic relates to the emerging UPV field. In Section 4 the findings of the review are summarised into four thematic research agendas and several research gaps for each are noted. The research gaps, in addition to the lack of connection between disciplines, also stem from the lack of connecting spatial scales, standardisation, life cycle, and microclimatic conditions. Additionally, limitations of the selected review approach and where other research topics may intersect with the focus of this research but were not included in the review are discussed in Section 5. Following this, conclusion to the study are presented in Section 6.

1.1. Contribution & novelty of this review

Through research contributions and reviews in the field it is now understood that UPV system design must specifically address the adverse effects that the conditions present in the urban environment (i.e. high temperatures, pollution, and shading) have on system performance [9,10]. Furthermore, the deployment of PV systems in urban environments require knowledge of multiple domains, requiring interdisciplinary planning [8]. To further support the growth of the research relevant to UPV this research reviews a broad collection of literature related to UPV to holistically describe the research landscape related to UPV and enable more interdisciplinary work. It was found that a wide variety of research domains contribute to the development of knowledge in the context of UPV.

This review is supported by the utilisation of data-driven techniques, further explained in the following sections. In this review latent topics in the publications that provide a basis for organising the multidisciplinary field and distilling knowledge about PV devices and systems in cities are uncovered. In reviewing content from each of the topics this review is able to form an overview of the research in field to determine several research topics for UPV. This research differs from previous studies through several aspects. To the best of the authors' knowledge this review encompasses the largest scope of research relevant to photovoltaic development and deployment specific to buildings and cities. This broad of a review is empowered by a proven machine learning method, Latent Dirichlet Allocation (LDA) that has been used as a method for urban and renewable energy review [11–14]. There are not many similar publications in the scope of PV and LDA with the most relevant being an LDA-based review of technology development of for solar energy [15].

While the LDA approach can be successful in organising documents with similar terminology it is not capable of providing structured and logical text analysis. Therefore a novel approach using a contemporary large-language model was used employed to name and understand the unstructured text data within each output topic. This was then coupled to a traditional review method in which highly topic-relevant literature was reviewed to more concretely understand the contents of the topics. The combination of these factors provide for a novel and innovative review approach as well as provide a new point of view for the literature relevant to UPV.

2. Topic modelling methodology

In this review a corpus of documents relevant to UPV research has been organised into topics using a data-driven approach to describe the range of work that contributes to PV research in cities and to understand where research gaps exist. For this task a workflow of text cleaning, vectorisation, and LDA was employed. This data-driven approach and specifically LDA was selected over a manual review due to the suspected broadness of the relevant research and because it was expected that there were themes that tie together the broad range (i.e. multidisciplinary) of research but understood that these may not be apparent from a manual review process.

In the following sections three major components of the topic analysis that is focused on the use of LDA implemented in Python through Gensim [16] are described. In Section 2.2 the search terms and databases used to compile the initial corpus of abstracts are introduced. Following this, in Section 2.4, the topic analysis methodology is introduced. Finally, in Section 2.6, the corpus is discussed in terms of time, as each month new relevant publications become available and need to be added to corpus as it evolves into an active database.

2.1. Data driven literature reviews

Machine learning and semantic analyses of academic literature are becoming a common form of engaging in the literature review process, as well as in continuous monitoring of the research published in an academic field [17]. These approaches provide the research with tools to catalog widely dispersed and rapidly growing publication fields. The rapid growth of literature on Severe Acute Respiratory Syndrome Coronavirus-2 is a practical example of how the approach was used to quickly organise an unprecedented development in research on the order of tens of thousands of new publications each month into topics for more straightforward consumption by medical professionals [18,19]. This form of literature review, done through topic modelling, is a method for discovering the latent points of discussions within a corpus of documents, those that exist but are perhaps not intentionally structured. The most common approach, LDA, is a method of natural language processing (NLP) in which a number of topics are predefined for a corpus of documents and each member of the corpus is assigned a probability of belonging to each topic [20]. The probabilities assigned to a corpus member are derived from the chance that collections of words within that member appear in another member. Each topic can then be described as collection of words that commonly appear together and not with other words. Grouping topics this way has been shown to outperform typical clustering algorithms such as K-means [21] and has been effective in summarising the literature relevant to research topics into more manageable data sets which can either be interpreted traditionally or through further computational techniques [22].

2.2. Corpus assemblage

The analysis was limited to journal articles, conference publications, and technical reports such as those available from The International Energy Agency Photovoltaic Power Systems Programme Task 15 Enabling Framework for the Development of BIPV. Publications were initially gathered from dates up until 1 December 2021. Publications from after this period and until 15 December 2024 were added to the corpus by applying the trained model to categorise them into one of the discovered topics. The following search terms using the application programming interface tools provided by OpenAlex [23,24] and The Lens [25] were used to access the content from the databases:

- bipv* OR bapv* OR (“building photovoltaic*”)
- (bipv* OR bapv* OR “building photovoltaic*”) AND (urban OR cit*)
- “solar energy” — AND morphology

2.2.1. Record cleaning

Once compiled the raw corpus of documents consisted of 3615 members. The raw dataset was assumed from the outset to contain irrelevant (e.g. wrong field), incomplete (e.g. missing abstract text), or flawed records (e.g. parsed from the original document incorrectly). Filtering for these types of documents led to a count of 3441 members. This cleaning process was conducted manually, through a review of the titles and of the word count of the abstracts.

2.2.2. Text preprocess

Before conducting the topic analysis the text associated with each corpus was compiled from the member’s title, keywords, and abstract. This string was processed to remove punctuation and stop words (e.g. “and” or “is”) using the spaCy English Language Pack [26]. Additionally several words or phrases were found in the abstracts that were added to a standard list of stop words. These include the original search terms from Section 2.2 and poorly parsed terms from the document such as “utc” or “</jat”. Further processing using spaCy included the lemmatization of the words (e.g. “sees”, “see”, “saw”, and “seeing” become “see”). The resulting array of terms for each corpus member were then stemmed using the Snowball stemming module of Natural Language Toolkit [27] to reduce their length and further consolidate unique terms into a more machine readable string. Then, all terms were tokenized (i.e. individual words) and unique terms were kept within each corpus member. This list of tokens was then fed to the LDA in the form of a “dictionary” which the LDA model transforms into a “bag of words” (BoW). Gensim was utilised for this process [28], and to implement LDA in the following sections. The BoW approach counts the number of occurrences of each word in an array and then converts the word to an integer word id. The result is a vectorised array of the original text string which is directly machine readable.

2.3. Topic modelling through latent Dirichlet allocation

LDA, as described by Hoffman and Blei [29], was implemented in this review to identify underlying topics within the corpus and provide a data-driven structure to organise the broad collection of literature before a manual review process. LDA is a probabilistic model and assigns each document in a collection of literature (i.e. a corpus) a probability distribution across a set of topics, whose count is predetermined. The allocation of topic relevance is determined by patterns in word co-occurrence. Each topic is represented by a group of words that frequently appear together, signifying specific patterns that are then treated as topics that exist within the literature without having been intentionally created (i.e. latent). This approach is particularly advantageous for an interdisciplinary field like UPV, where publications may span multiple disciplines and benefit from a model that reflects these overlapping themes. In Section 2.3.1 we describe the chosen parameters for the LDA implementation and in Section 2.3.2 we describe the crucial process of selecting the number of topics which are presented within the literature.

2.3.1. Topic model parameters

As mentioned, LDA was employed to model the topics from the corpus. In the following section the final topic number that was chosen is described. However, to arrive at that number, it was necessary to determine the LDA parameters. The LDA framework that was implemented is an out-of-the-box solution from Gensim [28]. After consultation with the Gensim documentation it was decided that the two key Dirichlet priors, “alpha” and “eta”, would be set to “auto”. For “alpha”, the “auto” parameter was chosen because in iterations of the run during development, when a small value was used for “alpha”, a restricted topic distribution was created. The interdisciplinary nature of contemporary academic work means that documents likely would need to belong or at least have some association with multiple topics. This is where the “auto” parameter is very successful. For “eta”, it was suspected from the beginning that some topics might share words which can cause issues if the word distribution per topic is too narrow or too broad. In these cases the “auto” setting can be implemented to allow the model to adjust “eta” dynamically, allowing the model to adapt whether topics need to be more specific or broader in their word distributions based on the data. The model was trained using a fixed random state (42) for reproducibility. The hyperparameters were set as follows following the documentation: “passes=30”-to improve the quality of topics and bring the model closer to convergence, “chunksize=4000”-the ensure the entire corpus was brought within a single chunk, “iterations=600”-to provide for stable and accurate topic distributions, “eval_every=None” was used during the final loop of topic number iterations to improve computation time.

2.3.2. Determining topic count

In LDA, the number of topics must be specified prior to running the analysis. Traditionally, LDA models are evaluated using a measure known as perplexity, however this has been shown to produce groupings of topics that while quantitatively optimal are not easily human-interpretable [30]. Another metric used in NLP to evaluate the quality and consistency of text or language produced by a model is coherence. It measures how well the words and sentences in a piece of text relate to and support each other, and how well the text flows and makes sense. In the context of LDA, coherence can be used to evaluate the quality of the topics discovered by the LDA model. Higher coherence scores indicate that the topics discovered by the LDA model are coherent, consistent, and well-structured, while lower coherence scores indicate that the topics may be disjointed, confused, or difficult to interpret. Coherence does not have a maximum value and is considered to be a relative measurement between iterations of the same model. Therefore the model with the number of topics that has the highest coherence value in a loop of LDA attempts using a range of topic counts was selected. In Fig. 1 coherence and perplexity values for the full range of LDA models based on different topic counts, indicating the maximum coherence value is shown.

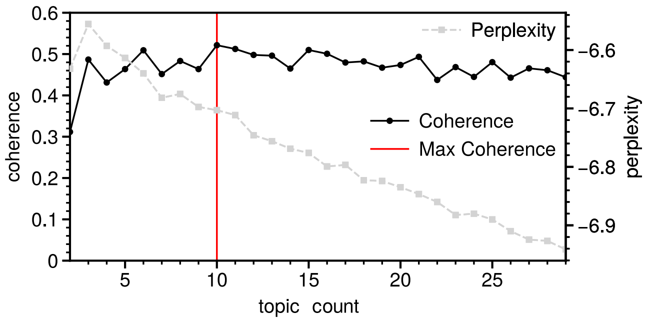


Fig. 1. The coherence levels for the different iterations of the LDA. Each row shows the association value of every member of the entire corpus to the topic for which the row is labelled.

2.4. Corpus topic analysis

As is shown in Fig. 1 the number of topics selected is ten, but the coherence value for this number of topics is not that distant from several other topic counts, such as six or fifteen. The final selection of topic count and the determination of the LDA model as "good" is somewhat subjective to the content and task at hand. This is discussed later in the review, in Section 4. The selected ten topic model was evaluated using the following guidelines:

1. Uniqueness: Are there a large amount of corpus members that are shared between topics?
2. Clarity: When looking at the text representation of the topics, do they make sense?
3. Coverage: Are there a large amount of corpus members that were not labelled under the selected topic count?

2.4.1. Uniqueness

The ten most relevant terms were extracted from the dictionary of each topic. Of these 100 terms, 31 are shared between topics and the term that is shared amongst the topics the most is "electr", which is shared four times. This term, being the stem of "electricity" and "electrical", is quite common in PV analysis of all forms and is therefore expected to occur multiple times. Furthermore, the other shared terms can be seen in Fig. 2 which depicts where terms are unique and for which topic they belong and where they are unique. The next most-shared terms are similar to "electr" in that they are expected them to arise in all publications, such as "cell" or "modul". Qualitatively, the uniqueness of words for each topic is acceptable as no overlap was found between all but some of the most common words.

2.4.2. Clarity

These same sets of highly relevant words can be used to check for clarity. The most relevant words for each topic should be similar in their meaning; the content of the topic should be noticeable when looking at the most relevant words. The highly relevant words for Topics 3 and 10 are shown as examples:

1. Topic 3: 'materi', 'temperatur', 'modul', 'cell', 'thermal', 'heat', 'chang', 'concentr', 'surfac', 'pcm'
2. Topic 10: 'power', 'modul', 'perform', 'dc', 'instal', 'oper', 'connect', 'grid', 'shade', 'model'

The meanings of the words are generally similar, such as in Topic 10 where the words all align with the subject matter of the power grid and power generation or in Topic 3, where words referencing material parameters and temperatures are the most common. This process was repeated for all topics.

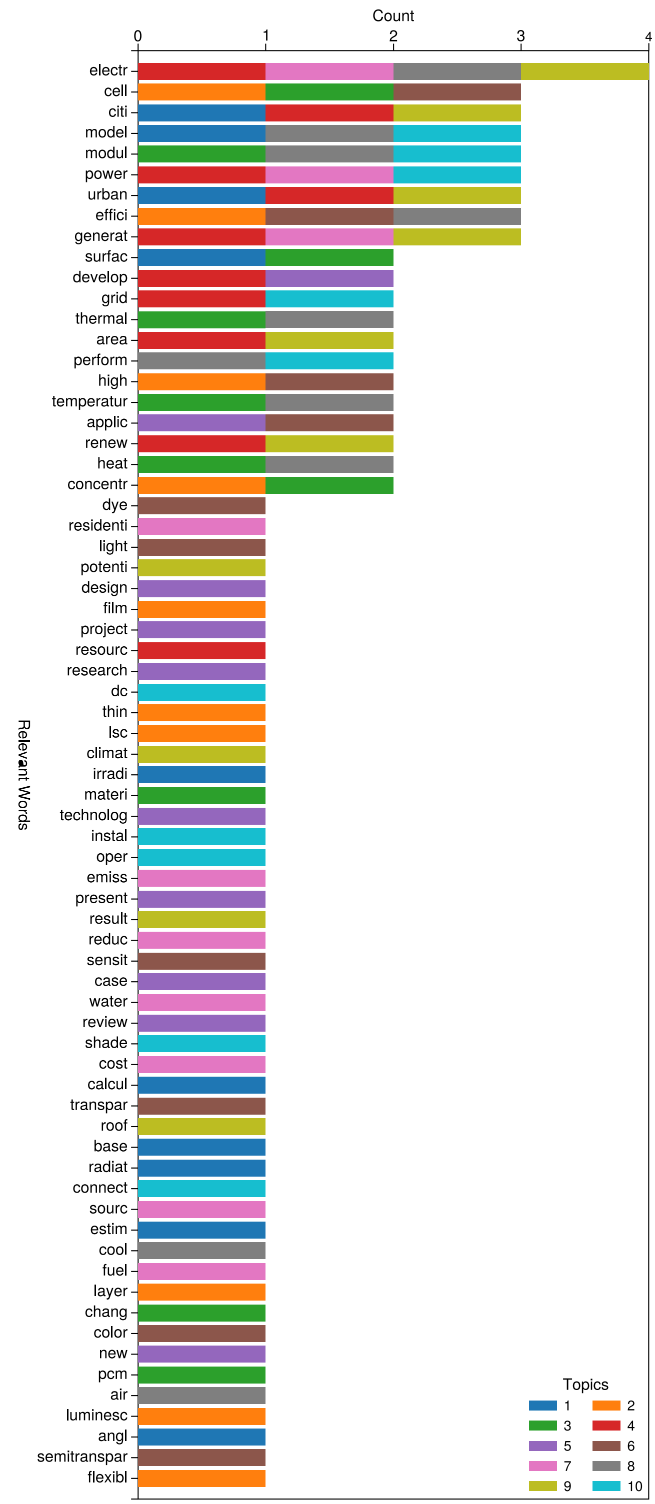


Fig. 2. The presentation of the most relevant words from the topic analysis and a bar representing which topic they appear in.

2.4.3. Coverage

In Fig. 3 the relationship of every member in the corpus to each topic is shown using a metric known as topic association score (TAS). TAS are assigned for each member in the corpus (i.e. each publication) through the LDA and exist between 0.00 and 1.00 for each of the ten topics. A TAS of 1.00 for a topic means that the corpus member

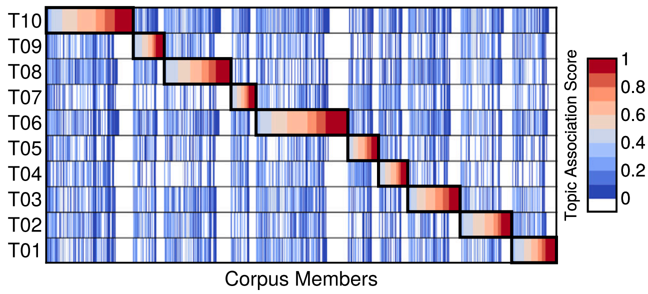


Fig. 3. The size of each topic shown via individual corpus members and their association with each topic.

Table 1
The titles written for the topics and the scored relevance to their topic, with 1.00 being the value of maximum relevance.

Topic name	TAS
Urban Solar Irradiation Prediction: Methods, Models, and Results	0.93
Evolving Technology (Thin Film and Concentrators)	0.89
Thermal Energy, Phase Change Materials, and Urban Heat Island in UPV	0.94
Potential of Integrated Solar Power to Meet Urban Energy Demand	0.91
Empirical Based Approaches for Successful Integrated PV Implementation	0.92
Dye, Organic, and Perovskite Solar for Transparency and Colors	0.91
Feasibility and Impact of PV for Sustainable Energy Generation In Cities	0.91
Design Parameters and Thermal Performance of BIPV and BIPV/T	0.90
Integrated PV Energy Potentials in Different Urban and Climatic Contexts	0.91
Effects of Shade, Electronics, and Controls on BIPV Modules	0.91

is solely related to that topic. A document with a TAS of 0.55 for Topic 1 and 0.45 for Topic 2 means that 55% of its content is aligned with Topic 1, and 45% is aligned with Topic 2, reflecting a mixed-topic relationship. This is problematic, but cannot be overcome and is discussed in Sections 3.11 and 5.1. An example of this is shown for several keywords in Fig. 4(a). In each row of the plot in Fig. 3 a single corpus member is represented using a thin vertical line which is coloured by its association score to the topic. For each topic the members of the corpus whose largest association score is that topic are grouped in the black boxes. It is important to note that this does not indicate the value is above 0.5, as the association score of a corpus member may be nearly equivalent to all topics. In total this group represents 18% of the overall corpus, a ratio that only rises with more topics and decreases with less before zeroing out at the two topic LDA. Of this 18% of the corpus, the majority of the maximum association values is more than 0.38, which indicates that while these corpus members cannot be related to a specific topic they are not necessarily without a category. Due the difficulty in resolving this portion of the LDA from a quantitative aspect, these corpus members were reviewed as an additional category of topics in Section 3.11.

2.5. Topic names

The topics were formed purely on the basis of this TAS assignment process and therefore do not come out of the LDA with semantic descriptions, just highly relevant words. Therefore the highly relevant words for each topic that were mentioned in Section 2.4.2 were also used to name the topics. For each topic OpenAI's Large-Language Model (LLM), ChatGPT [31], was prompted to determine 20 unique titles based on the 15 most relevant words for each topic. The names generated for each topic were then scored for their association to that topic at hand using the trained LDA model from the topic discovery process. Then several of the generated titles were evaluated manually to create highly relevant and coherent titles for the topics, the results of which are shown in Table 1 where for each title its association score to the documents in that topic is shown, with a maximum value of 1.00. These suggestions were reviewed manually to compose a final title. The entire process is presented in Fig. 4(b).

2.6. UPV database and semantic model

The records for the original corpus were extracted from the academic databases until 1 December 2021. As related work is published consistently and work outside the search queries or databases can be uncovered, the trained LDA model was employed as a classifier for adding newly published papers to the corpus under the identified topics. The addition of 535 documents that were published or emerged between 1 December 2021 and 15 December 2024 into the database was used as an opportunity to examine the human interpret-ability of the topics. The title and abstract of each of the 535 new additions were reviewed and a topic number that was assumed to be the most representative (as the LDA model would assign) was given to the topic. These assigned numbers were then compared to the LDA model's evaluation. The classification proved to be correct roughly 67% of the time and most often the correct topic was stated as the second or third most relevant topic . A final depiction of the corpus size can be found in Fig. 5.

2.7. Interpretation of the data-driven review

While it was expected to find connections between the literature through the LDA, it was also expected that these may not be useful for communicating research gaps and trends or there would be too many connections and themes to realistically review. Therefore a synthesis process was planned for the resulting LDA-organised literature. The analysis of the data-driven review was used for a further distillation of the research landscape into six thematic research agendas, which are discussed in Section 4. This process involved reviewing the content of the ten identified topics and the mixed topics. Each topic was examined to extract core themes, insights, and research gaps. These findings were then synthesised and refined into the overarching research agendas that encapsulate the critical issues and opportunities across the domain. During this distillation, the focus was on identifying common threads across the topics, while ensuring that the unique contributions of each subtopic were represented. In addition to the structured review, supplementary research not previously captured in the topic analysis was incorporated using a Snowball approach for recent work.

3. Review of ten research topics on urban photovoltaics

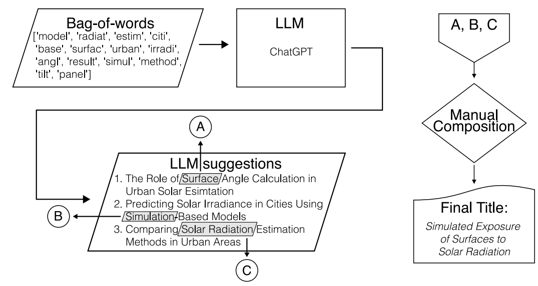
The final corpus was comprised of 3686 members across the ten topics between 1970 and 2023. In the following sections the contents of each topic are summarised through a review of a portion of the publications within each topic. An overview of the ten topics is shown in Fig. 6, grouped into the five larger themes "simulation", "technology", "thermal", "system" and "society".

To reduce the total time for reviewing papers and to keep this research concise, only 10% of the publications with the highest TAS scores within each of the ten topics were extracted from the corpus and reviewed in Sections 3.1 through 3.3. In the research 10% is considered to be the central works representative of the general themes that are present within each topic. Lastly, In Section 3.11 a special collection of publications was reviewed. These corpus members did not have a TAS for any topic above 0.50. For this grouping a set of publications with the most citations per year was reviewed.

For each topic the papers were reviewed in chronological order and for each publication the abstract, introduction, and concluding remarks were all read. Subjecting the scope of the review to this lens allowed us to describe the topics through their content and understand the state of knowledge within each of the topics. From these summaries several research agendas were uncovered that are being pursued in the field. These are discussed in Section 4.

	Campus and...	Solar collectors...	Whole systems...	Improved electrical...	BIPV hotspots...
T1	0.00	0.00	0.00	0.02	0.01
T2	0.00	0.00	0.00	0.02	0.01
T3	0.00	0.00	0.00	0.02	0.01
T4	0.55	0.00	0.00	0.02	0.02
T5	0.00	0.19	0.97	0.03	0.87
T6	0.00	0.00	0.00	0.02	0.01
T7	0.00	0.00	0.00	0.02	0.01
T8	0.00	0.78	0.00	0.82	0.02
T9	0.42	0.00	0.00	0.02	0.02
T10	0.00	0.00	0.00	0.02	0.02
Topic	3	7	4	7	4

(a)



(b)

Fig. 4. (a) An example of the Topic Association Scores (TAS) for each topic (rows) assigned to several studies (columns) through the LDA process, indicating the primary topic for each (footer). A large TAS, shown in green, indicates a high match. (b) The process of naming one of the topics using the unstructured list of relevant words and the suggested names from the LLM.

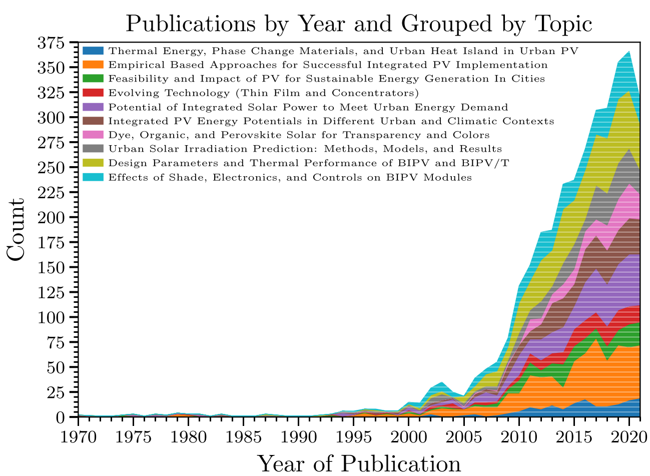


Fig. 5. The growth of the overall corpus separated into each of the topics. While the corpus contains members published after 2021, these dates were excluded due to a general delay in publishing which leads to the tail of the plot being illegible.

3.1. Topic 1: Urban solar irradiation prediction: Methods, models, and results

The research associated to this topic is key to being able to simulate the performance of PV systems in complex urban environments. Central works within this topic were mostly published after 2009 and all generally discuss research focused on either modelling solar irradiance in urban environments or on how to maximise a surface's solar potential. Twenty-seven papers were gathered through the filtering process and reviewed. The work ranges from 1973 to 2021 and was found to have a small range of subtopics: modelling solar radiation, transposition for surface irradiance estimation, modelling scenes with high degrees of shading, and the optimisation of surfaces for maximal insolation.

Primarily the work was concerned with different methods for solar radiation estimation in urban building contexts through either correlation or regression of empirical data. The research makes use ground-measurement data such as global horizontal irradiance or air temperature to determine solar radiation profiles for a give location [32–34]. However, some of the work is focused on characterising solar radiation for a location using remote sensing technologies [35,36]. Furthermore, several papers focused on adapting existing models for inferring solar radiation from other meteorological traits such as humidity and air temperature through correlation or developing machine learning models, primarily Artificial Neural Networks [37–41]. From a methodological point of view, global solar radiation is commonly taken from meteorological stations and converted to plane-of-array irradiance using one of several transposition models [42–44]. Ray-tracing of a 3D model was employed in few studies [45–47]. In some cases the use of clear sky models replaced the input of measured global solar radiation data [41,48,49]. A second half to the topic might be considered as research focused on the receiving end of the irradiance modelling task. In several works there was an attempt to characterise shading or understand how to mitigate its impact on a surface [46–48,50–52]. Similarly, the remainder of work is focused on maximising solar potential of surfaces through tilt and/or azimuth optimisation [42,52–54].

It should be noted that this review does not include a state-of-the-art frame, merely a characterisation of common research topics through the NLP approach. Thus, and particularly for this section, certain key works are missing from this topical review.

The first group are physically-based approached which stream from the raytracing simulation suite of Radiance [55] and the Perez sky model [56]. Combined these have been implemented in a multitude of simulation toolsets such as Radiance itself, Daysim [57] and the 2-Phase Daylight Coefficient [58], the City Energy Analyst [59], and the Urban Modeling Interface [60]. While computationally expensive these methods have been shown to scale from interior daylight rendering to urban irradiance estimation.

The second group is that of machine learning based approaches. In this topic, models are trained using large datasets to predict either point-in-time irradiance or generate irradiance time series. In the work from Walch et al. [61] a country scale assessment of rooftop irradiance was conducted suing a variety of different machine-learning frameworks, with Random-Forest Generation proving to be the most accurate. More recently Zhang et al. [62] were ablate implement a Generative Adversarial Network approach to generate annual hourly timeseries for facade sensor points in an urban 3D environment.

Given these additions a brief summary of the methodologies seen across this topic are as follows:

1. The characterisation of global irradiance for a specific global point and surface normal either using measurements, regression, a combination of the two, or machine learning methods.
2. Ranging from simplistic transposition models to ray-tracing one approach is the transfer of irradiance measurement date for a geographical location onto a surface such as a rooftop or a facade.

The literature reviewed features a breadth of methods for assessing surface effective irradiance, the first step in the simulation of PV output. In this, discussion two classical computational research factors relevant to UPV in the irradiance modelling space can be detected. First, how to most accurately model contextual shading such as urban furniture (i.e. poles, benches, transit stops) and vegetation. Second, how can the simulation phase be sped up as questions of PV productivity in urban spaces often require the assessment of a significant amount of surfaces.

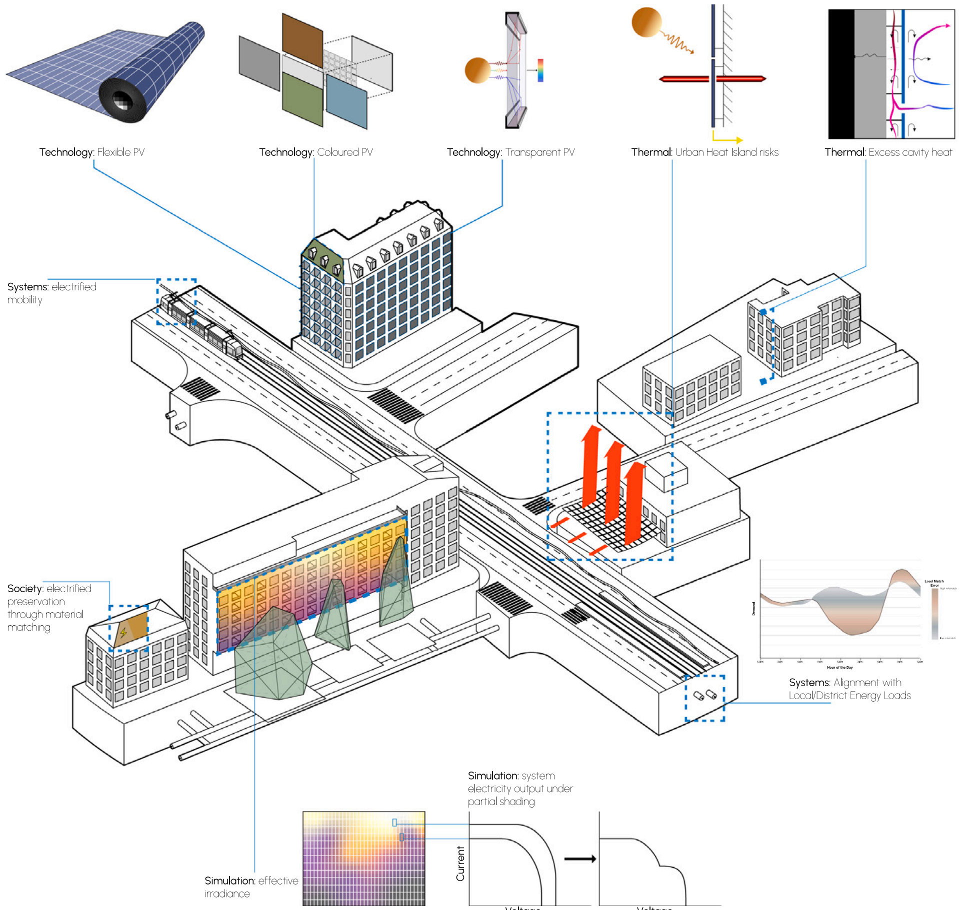


Fig. 6. A thematic overview of the ten topics that were uncovered through the review. Topics cover a variety of scales and potential applications within the built environment. Here various PV technologies, simulation practices, micro-environment interactions, and connections with transit and district energy are shown.

3.2. Topic 2: Integrated PV energy potentials in different urban and climatic contexts

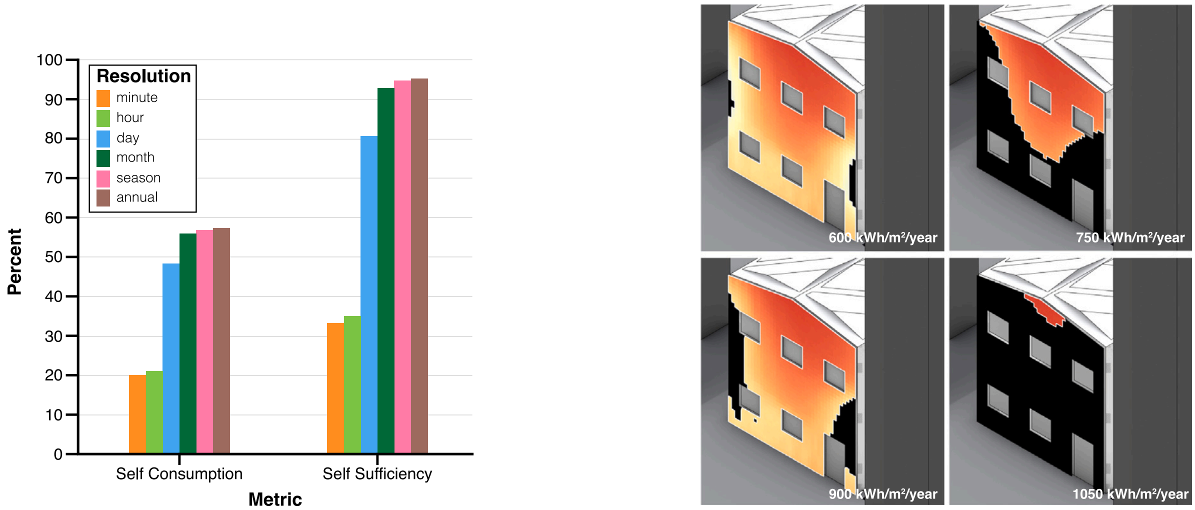
Where Topic 3.1 ends this topic resumes with assessment methodologies of PV electricity output potentials in urban contexts and the methods behind these assessments. The research within this topic differs from the previous in that it does not focus on the models and methods for simulating solar exposure or effective surface irradiance. However the research within this topic does include mention of these aspects because they are necessary to provide input for PV models. Of the 35 papers collected, four were removed due to either a lack of access or not being published in English. The remaining papers can be separated into three primary groups. First, those that propose some form of a framework for modelling and assessing PV potential, specifically for urban context. Second, those that evaluate or optimise PV module placement on urban buildings. Lastly, research in which PV electricity is simulated for a variety of scales is seen.

Within the first group there are five papers, all which are written to expose a new framework or specific method. Bergamasco and Asinari [64] present a method for estimating electrical energy output from roof-based PV systems across a large region in Italy. Gooding et al. [65] describe a method to extract roof geometries from LiDAR point clouds for solar potential assessment. Hassim et al. [66] assess the utility of freely available evGeographic Information Systems data for assessing solar energy potentials in informal settlements. Shirazi et al. [67] provide a detailed description of a tool to model building integrated photovoltaic (BIPV) arrays on building facades and rooftops and assess their electrical potential. Lastly, Wang and Cao [68] provide a method to optimise urban building energy performance based on PV productivity using Laplace transforms.

In the second group several subgroups can be formed. In the first, the research focuses on the description of roof geometries using LiDAR data [69–71], with Sanchez et al. [71] evaluating several input resolutions for the point cloud and determining that one or two points per square meter is sufficient to model roof geometry for solar radiation analysis in cities. In the next group the research is focused on the use of measurement data to understand energy generation potential in cities. Here the the research describes how ground measurement data was used to assess the viability of various PV systems in urban settings [72–76].

The last group is the largest collection of papers within the topic where the research is focused on simulation-based assessments of PV potentials for buildings [77–79], urban districts [80–84], optimising urban form [85–87], or optimising architectural properties [88–92]. Methodologically speaking the research tends towards analysis done using monthly or annual time resolutions, which was shown in Ordenes et al. [77] to be too coarse of a time resolution to accurately depict self consumption rates of PV-electricity. In Fig. 7(a) an example of self consumption and self sufficiency rates calculated at different temporal resolutions using reference data from a monitored residential building in [63] to describe why coarser resolutions are not as effective as more precise is shown.

A common thread to many of the cited literature was the use of an irradiance threshold to determine which surfaces were viable candidates for PV integration. In Fig. 7(b) a depiction of this selection based approach can be seen to reduce the available area substantially. This concept can be traced back to Compagnon [93] which is not included in this topic or the larger corpus. However, in the research, a threshold is employed $[\frac{\mathrm{kWh}}{\mathrm{sqm}}]$ that was determined for their region in



(a) (b)

Fig. 7. In (a) data from [63] was used to calculate self-consumption and self-sufficiency rates at different temporal resolutions. In Figure (b) the impact of increasing the irradiance threshold value for determining the placement of modules is depicted.

order to reduce the number of surfaces that had to be simulated. This number was derived from discussion with experts in the field based on local technical and economic barriers. Defining location and context specific methods for determining the appropriate threshold should be considered as a larger research agenda as the metric is useful for project planning.

The research in this topic focuses on the development of more accurate, fast, and larger scale models for urban PV-assessment. The following findings from the review:

1. Urban PV assessment depends on either collecting data from several sites in the area of interest or establishing a spatial model to first conduct irradiance and shading analysis which can then be used to PV electricity output modelling. The results of these studies tend to be specific to the context of the research and more work is necessary to aggregate general design guidelines on a larger scale (i.e. best practices for UPV design).
2. The majority of simulation-based research at larger spatial scales tends towards coarse temporal resolutions which may not be sufficient for calculating self consumption ratios in buildings and urban energy districts.
3. The use of a static irradiance threshold value to remove potential surfaces from assessment pipelines is not used according to the original literature and should be considered more dynamically based on regional traits such as the grid electricity carbon intensity.

From this review the research finds that the state of UPV modelling and simulation is still nascent, holding to lower resolution methods to reduce computational expense or complexity. Additionally, while not central to this topic the accuracy of PV potentials assessment is tied directly to the assessment of surface effective irradiance. Across the reviewed papers a full range of approaches was found that were presented in Topic 3.1 and little discussion or rationalisation of their application given the context of the research subject. Lastly, the application of methodologies and assumptions from different scales or locales, such as the solar-availability threshold, can lead to results that may be too simplified or are difficult to compare across studies.

3.3. Topic 3: Effects of shade, electronics, and controls on BIPV modules

In this review of 38 publications central to this topic, of which two were removed due to lack of access to the full text version of the research, a collection of papers in which the research describes the performance of PV systems in terms of their power electronics is found. Several subtopics are found: electrical topology analysis, maximum power point tracker algorithm development, power electronic construction, and performance models and systems tracking methods.

For the design of the system several topologies are described through multiple papers, with a general description of seven systems found in Liu et al. [94]: (a) centralised system, (b) multi-string system, (c) string system based on generation control circuit, (d) string system based on bypass direct-current to direct-current module-integrated converters, (e) cascaded system, (f) alternating-current module technology, and (g) direct-current module technology. Here the research finds that (f) and (g) are the most suitable for BIPV applications due to their robustness in conditions where partial shading is present. This evaluation is echoed in other work in the collection [95–100].

Operational studies are largely concerned with MPPTs and other current/voltage regulating methods. The focus of many of these is to improve maximum power point tracker algorithms and controller performance under less than ideal circumstances such as partial shading, which is largely an objective for much of the research within this topic. Multiple papers introduce improved or new algorithms for module-based MPPTs [101–108]. Several papers introduce or discuss power electronics development for BIPV operations specifically, including low-voltage power optimisers and physically smaller inverters to fit into wall cavities [95,109–114]. Performance models for PV systems range in scale and applicability for this topic [115–117]. In some cases these are developed through empirical correlation [118,119]. Further analysis and system performance is undertaken for a variety or reasons including shading analysis [120], financial modelling [104,121,122], and general system diagnostics [123–129].

The impact of partial shading and the design of electrical topologies is of significant importance to the success of a UPV system which can experience high degrees of partial shading with the central findings distilled:

1. Research on electrical topologies and partial shading is typically done by groups in the electrical engineering fields with recommendations for design and planning of systems being a part of the research outcome. However, of the reviewed work only one focuses on topologies and partial shading beginning from a multi-building or urban perspective.
2. The impact of partial shading and the design of electrical topologies is of significant importance to the success of a UPV system which can experience high degrees of partial shading.

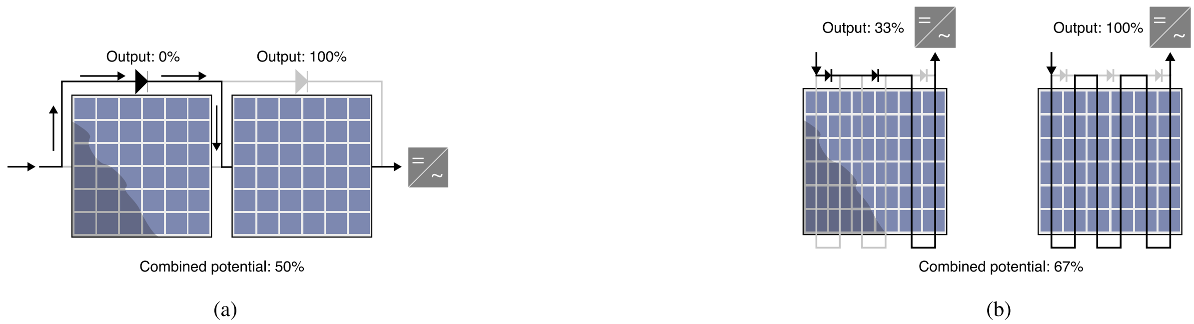


Fig. 8. Here the impact of partial shading on a PV module string (a) and two PV modules both utilising microinverters (b) is shown. In (a) the activation of the bypass diode (dark black lines) leads the total system to lose half of its potential, while in (b) the system still maintains a third of the output of first panel for a larger combined output.

3. Across the studies the impacts of partial shading lead to annual Performance Ratios between 20% and 30%. Mitigation techniques from an electronics point of view tend towards module-level optimisers of microinverters, but several papers note that most mark-et available technologies are not prepared for BIPV specifically.

The literature found in this topic makes clear the impact of partial shading on PV productivity. Also there is a clear argument for future research to focus on the development of methods for enabling designers to work with simulated partial shading to optimise their designs. Furthermore there is a focus in the literature on the development of systems and module technology that can prevent the high degrees of loss due to partial shading that is depicted in Fig. 8. The review finds that the impact on PV productivity due to partial shading and cell or module mismatch within a string can vary widely amongst the published results, ranging from 5.0% to 70.8% in [96]. This wide range can be attributed to the type of shading present, the electrical topology of the PV system being assessed, and the PV modules used in the study. Conditions within cities are highly irregular and in order to conduct more consistent studies it may be necessary to characterise standard shading conditions with which to conduct partial shading analysis amongst technology and system variants.

3.4. Topic 4: Evolving technology (thin film and concentrators)

Two distinct topics emerged that contain research on PV cells and sub-module design and engineering. In the first, which is focused on thin-film and luminescent solar concentrator based technology, the advantages of which can be seen in the diagrams of Fig. 9. Twenty-two papers were collected from the filtering process, of which three were removed due to a lack of access to the full print version of the research. The work ranges from 2012 to 2021 and covers a section of solar cell science devoted mostly to amorphous silicon (a-Si) and hydrogenated amorphous silicon (a-Si:H), copper indium gallium selenide, luminescent solar concentrators (LSCs), and optical films for thin film devices (i.e. colour films).

Experimental methods pertaining to device fabrication and characterisation using either spectroscopy or current–voltage curve analysis. In this area there is little computational assessment of devices, with only a few papers describing computationally modelled versions of their devices [130–132]. While the scope of the topic is largely focused on thin film devices the actual topics are diverse. Research ranges from novel device characterisation [133] to the improvement of specific components such as inverters [134,135] in specific module constructions to structural and material durability [130,136]. Lastly, many papers focus not on whole cell structures, but only a single layer [137,138] or the fabrication of cells [139] which is expected due to the incremental focus on improvement that this area of research has achieved.

While UPV is not the focus of work in this topic, some research brings up BIPV as a motivation [130,134,135,140,141,141–143]. Additionally, the advancements made in evolving technology that are discussed here have applications such as durability through self-healing [136,144], surface coatings [140,143,145], flexibility [130,140,146,147], and solar windows that are key to UPV [135,142,148].

This review has helped to build an understanding that in the research developing novel materials for PV or improving existing materials for specific products are interested in having their research considered for BIPV applications with the core findings:

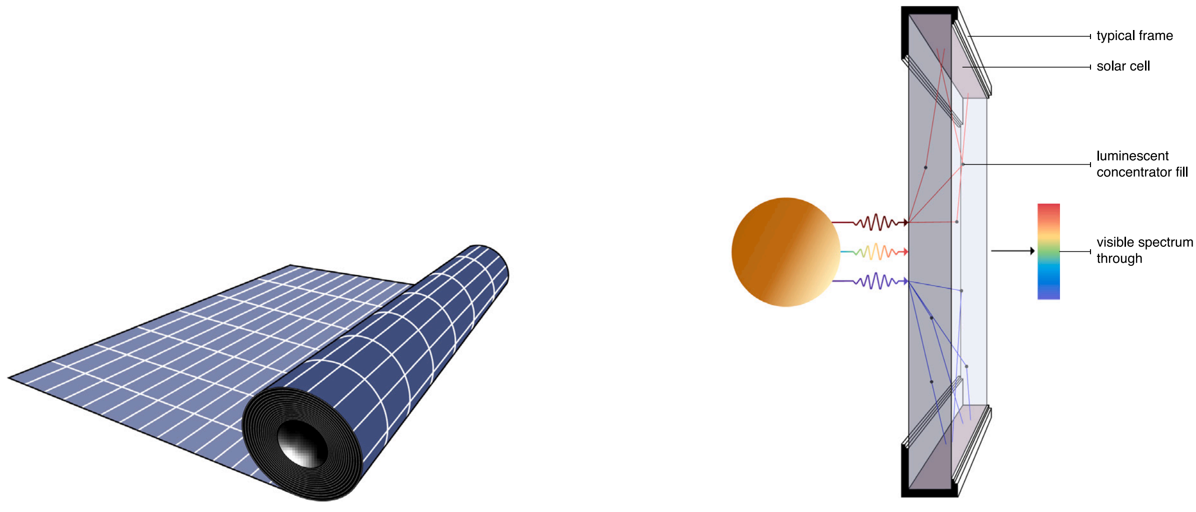
1. Durability and flexibility are the key focus of many publications. This ranges from a focus on cell-specific characteristics of module construction.
2. Research on these types of devices is conducted using physical experimentation and measurement rather than purely simulation due to the difficulty in simulating processes at this scale.
3. The majority of the research is focused on the improvement of specific components or layers within a device, rather than a whole device.
4. The research originates from material science and similar scalar approaches. A technological review of solar cell materials from the perspective of BIPV or UPV research was not found.

The research found within this topic is highly specific to several PV technologies, but could potentially impact the types of PV technologies used in cities. However, the research present in this topic is isolated from the literature of the larger urban and building scale topics. This matter will be discussed later in the review, but it is suggested that future research look into the connection of material and device level knowledge and urban-scale PV assessment. This is due to the benefits of these advanced technologies specially for building-based applications such as windows or curved surfaces.

3.5. Topic 5: Dye, organic, and perovskite solar for transparency and colour

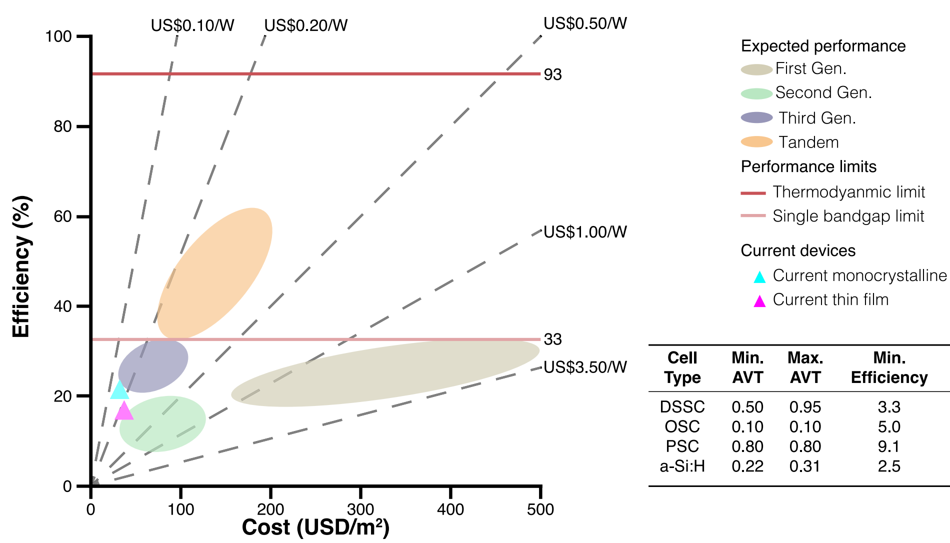
This topic differs to the previous one in that it excludes research on thin-film PV and LSCs, and focuses on so-called Third Generation solar cells, which are described relative to the First and Second generations in Fig. 10. In this section 24 papers are reviewed all concerning Third Generation solar cell developments. Eleven of the papers are focused on dye-sensitized solar cells (DSSC), five on organic solar cells (OSC), and six on perovskite solar cells (PSC) devices. The other two relate to a-Si:H.

The primary goal of research in this field is to improve solar cell performance (i.e. power conversion efficiency, cell stability under non-standard test conditions, transmissivity, and tunablity) by manipulating one or multiple layers within the solar cell [150–163] or by focusing on the fabrication process [164–168]. Durability/stability are a primary concern only in two papers [154,169]. The majority of the publications focus on the transparency and relationship of the solar cell



(a)   (b)

Fig. 9. Evolving PV technologies enabling new opportunities in architectural construction and design. (a) A roll-able PV module which is enabled by the development of flexible solar cells. (b) A luminescent solar concentrator that is able to harvest solar energy from the non-visible portions of the spectrum through, while transmitting visible light to an interior space.



Cell Type	Min. AVT	Max. AVT	Min. Efficiency	Max. Efficiency
DSSC	0.50	0.95	3.3	8.2
OSC	0.10	0.10	5.0	10.0
PSC	0.80	0.80	9.1	15.1
a-Si:H	0.22	0.31	2.5	6.4

Fig. 10. The expected benefit of third generation solar cells is higher efficiency at a lower production price, as well as semi-transparency, colour tunability, low weight installations, and flexibility. This chart was originally produced in 2001 by [149], but has been updated to include price estimates for contemporary modules based on spot price data from PVinsights for 2023-07-26 (monocrystalline 0.151 $\frac{\$}{W_p}$ and thin film 0.210 $\frac{\$}{W_p}$). The table shows the range of reported actual visible transmittance and conversion efficiency values for each cell technology.

to the visible spectrum (for colour tuning). This scope reinforces the understanding that the papers in this topic are mostly related to the architectural-aesthetic of solar cells. However, some of the research is directly applicable to the design of solar cells that perform well in the irregularly-irradiated conditions of urban spaces [151,156]. Achieving an actual visible transmittance of 0.2–0.3 appears to be what is considered necessary in this field for to have a solar cell applicable for a window [170]. Of the reported values many solar cells are able to reach this level (see the table in Fig. 10). However, this does not indicate the entire picture of semi-transparency or utility in a window, in which colour and clarity also play a role. Chiang et al. [171] describe a DSSC with no colour distortion. Yu et al. [155] describe an OSC with a colour rendering index of 91 and an efficiency of around 5%. Pandey et al. (2020) [160] describe a DSSC that uses near-infrared dye to achieve an efficiency of 6%.

Lastly, two papers discuss their research not in the context of the solar cell, but rather the module. Hinsch et al. [172] describe a full-sized (60 × 100 cm) DSSC module that is capable of 2.3% conversion efficiency and offers semitransparent and colour properties. Lee et al. [173] review OSC research to provide a cost estimate of a representative OSC module.

The research reviewed describes developments in the space of Third Generation solar cells:

1. While durability and stability are the primary concern of only two papers, much of the research notes that this is important for the progress of their own work. This is particularly the case for PSCs which require more toxic materials for higher stability.
2. Despite sharing the same classification as Third Generation, this group contains several types of cells with varying properties and in reviewing the work it was found that the multitude of cell types carries with it specific applications that each is designed for.

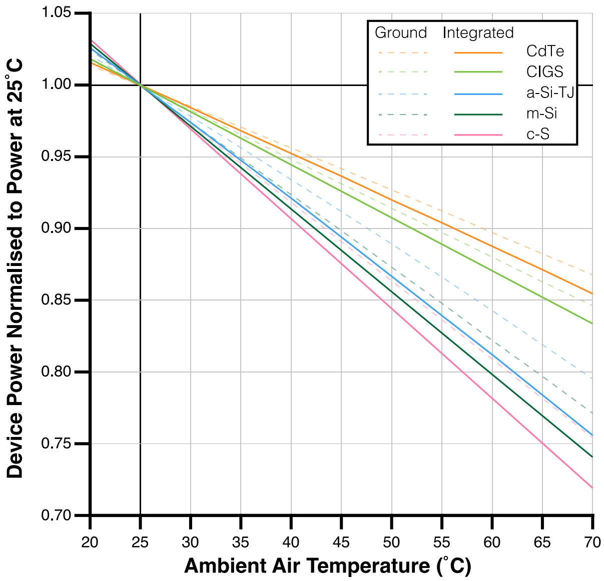


Fig. 11. The impact of higher back of module temperatures on potential performance for several types of PV cells calculated using the Single Diode [174] approach under 1000 $\frac{W}{m^2}$ irradiance and based on the a cell temperature model [175] which allows the modeller to differentiate between freestanding systems and those mounted nearby to facades or roofs.

3. Third Generation solar cells offer a pathway towards PV modules that can be used as building windows. While existing technologically can achieve the desired minimum levels of visual transmittance additional research points to colour tuning and clarity as future pathways for research.

Third Generation cells may still be deemed as experimental technology due to issues related to durability. However, it is apparent that there is an arc of development within the research that points towards commercialisation of these technologies. Commercialised devices such as PSCs or OSCs offer unique benefits to UPV through high levels of conversion efficiency, optical tunability, and transparency. Research in the UPV space should be sure to consider advancements in this field as longer term scenario planning studies are conducted for system deployment.

3.6. Topic 6: Design parameters and thermal performance of BIPV and BIPV/T

The focus of this topic is on the thermal performance of integrated PV modules and related envelope design characteristics. The relationship between heat and device performance is shown in Fig. 11. The majority of the 53 papers reviewed relate to BIPV and coupled thermal (BIPV/T) systems, i.e. BIPV that has been integrated into a larger network of thermal flows. In BIPV/T the waste heat from the PV modules is harnessed via a medium, often air or water on the module backside, and used for another purpose. This has been shown to increase system efficiency due to lower cell temperatures among other benefits, but the usefulness can depend on the mounting strategy. In Fig. 12 various conditions and mountings found during the review for PV, BIPV, and BIPV/T systems are shown. The majority of the papers can be organised by their methodological approaches.

There are two comprehensive reviews specifically collecting research on BIPV/T and their applications in architecture [176,177]. The majority of the remaining papers either employ simulation, analysis of an experimental setup, or a combination of the two. E.g., Chen et al. [178] focused on the use of fibre optic cables to transport light through a building into an interior room to provide daylighting and

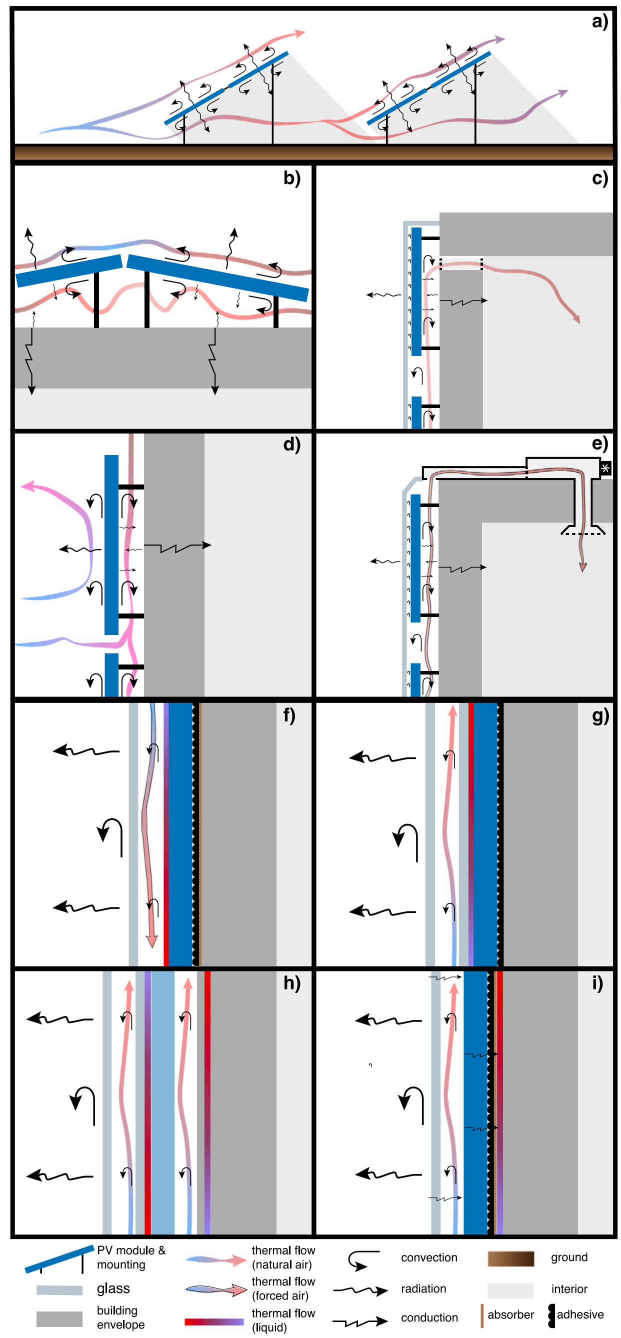


Fig. 12. PV, BIPV, and BIPV/T configurations found in the literature are shown: (a) ground mount array, (b) rooftop attached array, (c) double-skin BIPV/T facade with natural airflow, (d) BIPV facade, (e) double-skin BIPV/T facade with forced airflow, (f) free-flow BIPV/T, (g) channel BIPV/T, (h) dual-absorber BIPV/T, (i) sheet-and-tube BIPV/T.

then irradiance to a PV module, and Ju et al. [179] use an experimental setup to test the radiative heat flux of a burning BIPV module. The remainder all focus on BIPV/T for heating and cooling applications or reducing the operative temperature of BIPV modules. The proposed and analysed BIPV/T systems all operate using either water or air, except for one that is based on a refrigerant system [180]. Several others are connected to Trombe walls [181–183]. Fluids in BIPV/T systems are studied using air in natural or forced convection [184–189], while several employ water [190–194].

Two papers focus on systems that change their operation with the season. Saadon et al. [195] simulate a BIPV/T facade with forced convection during the heating season and natural convection otherwise. Xu et al. [193] propose a system that uses water for most of the year and switch to an air-based system in winter to improve seasonal performance. The forced convection-based systems are often simply connected to a variable-speed fan to simulate forced air operation [196–200], but several design experimental setups or simulations in which the BIPV/T is connected to an air-handling unit that controls the flow rate [201–205] or heat recovery system [206,207]. The air-handling unit systems are shown to increase performance [208], however the load of the fans is not well described as a load on the generated power. In some cases corrugated metal sheeting was applied in the air flow channel and shows improved thermal and electrical efficiency in the system [197,199,209].

Research that is not focused on BIPV/T is centred around the impact module design variations have on module temperature and performance or observing how module temperatures changes under different conditions [52,210–215]. Several pieces research recognise the need for an improved model for predicting BIPV temperature and attempt to propose such a model or correlation coefficients for existing heat transfer models [216–218]. Sellami and Mallick [219] design a concentrator structure within a window to increase light intensity on small PV cells, arguing that it can increase the daylight availability through BIPV windows without compromising output. Joseph et al. [220] study the spacing of cells in a semi-transparent skylight to determine the impact on daylight availability, module temperature, and room temperature. They find that more spacing improves the performance of the module due to less heat gain directly on the module. Qiu et al. [221] describe a vacuum insulated BIPV window which, in the context of building cooling demand, performs better than similar non-PV based fenestration systems.

The majority of the research is agnostic to the location with only a few papers specifying their location and tying it to the results [192,195,205,222–225]. However, it was identified that BIPV/T performs better in warmer climate than in moderate climates [191]. Design parameters for BIPV and BIPV/T systems are often a focus. For facade mounted systems with natural convection it has been shown that a primary parameter for performance is the size of the air gap, which is often stated as optimal around 10-cm [189,200,226]. No comprehensive analysis of this exists for multiple climates, module types, or mounting positions. One study reported 30 cm in tilted roof system as optimal [227], and another 50 cm for a Trombe wall based system [181]. Another parameter is the length-to-width ratio of a BIPV/T facade system, where length describes the vertical spacing between the inlet and outlet of the cavity. This is typically reported at 2:1 with a maximum of 3:1 [193]. The last parameter to focus on is the bottom inlet opening, it was found to be more effective in natural convection systems if this opening is larger than the top [189].

The focus of this topic is concentrated around heat removal/transport in BIPV systems. This allows use to draw more specific conclusions about the state of the research:

1. It is well known that mitigating heat in PV systems improves their performance and there are many solutions to solving this. However, the evidence from the research shows that this type of work can be sensitive to the location. Thus the review finds that one potential research agenda would be determining PV heat mitigation techniques depending on climate zone.
2. There is a large quantity of research on BIPV/T with several different formats for integrating thermal harvesting aspects, either through air or fluid based flows.
3. BIPV modules are heat-intensive building products. Therefore a research pathway for BIPV is the development of an accurate temperature model that is as computationally-efficient as existing empirically derived PV temperature models which do not rely on computational fluid dynamics.
4. The large quantity of research on this topic has led to a consensus that natural convection-based BIPV and BIPV/T should have an air gap of around 10 cm to maximise heat flow and that BIPV/T systems should operate in a 2:1 length-to-width ratio.

Existing data on PV modules and excess heat has been largely gathered from larger PV array systems. The differences in these contexts to the those found in cities calls into question the utility of derived models and knowledge. Additionally, the research reviewed suggests that not all principles should be considered to be universally applicable as location can influence PV performance and heat. Lastly, the harvesting of heat from integrated PV systems in particular has received a significant amount of attention in the literature, but primarily from a device construction scale. The integration of BIPV/T systems is not seen from an urban modelling perspective.

3.7. Topic 7: Thermal energy, phase change materials, and urban heat island in UPV

In this topic 18 papers were selected and two were removed due to lack of access to the full document or being mischaracterised as a PV-related publication by the search. In the review of the sixteen publications works focused on thermal regulation and heat mitigation either to combat Urban Heat Island (UHI) or to reduce the operating temperature of power electronics, PV included were found [228,229]. While it may appear similar to Topic 3.6 due to several shared keywords (e.g. thermal, heat), the research found within this topic is unique through its focus on UHI, Phase Change Materials (PCMs), manufacturing methods, and transparency. The research within the first group, focused on UHI is not centred around PV heat, but rather UHI mitigation in general where the impact of UPV systems remains an open question. The second group of research is concerned with tuning existing solar cell materials to provide less resistance and thermalisation to reduce operating temperature and, consequently, conversion efficiency.

Regarding UHI, Park et al. [230] found through remote sensing analysis that urban cores are warmer than neighbouring rural areas and forests. They suggest that the treatment of surfaces in these areas is paramount to mitigating UHI. Both Levinson [231] and Cheela et al. [232] explore mitigation measures for surface reflectance, but neither mention photovoltaics.

Some of the research of in this topic centres around the manufacturing and construction of modules. Several discussed custom module and cell manufacturing as well as front films and colouration of PV [233–235] (shown in Fig. 13(a)), showing that a diversity of performance characteristics are to be found with different colours. In Bruckert et al. [236] report on different solar cell cutting to improve the availability of shapes for manufacturing non-standard modules. Lee and Kim [229] report on the manufacturing of BIPV cells with specific material layering to improve near-infrared harvesting capabilities for BIPV windows.

Lastly, the final group were those focused on the use of PCMs in PV devices [115,237–241]. The remainder were interested in transparency and the use of PVs in glazing systems [235,242,243].

This is less consistently focused topic than others with three main subtopics being discussed:

1. UHI and microclimate interactions are mentioned in this topic, but a deeper understanding of the impact of BIPV on the urban microclimate and vice-versa is required. Sailor et al. [9] discuss these topics and review existing literature, but point out that the topic is highly regionally specific and should be addressed as such.
2. A variety of manufacturing techniques exist for coloured and non-standard modules, but the literature indicates that this type of module development remains expensive due to the reliance of the PV market on standard manufacturing pipelines.

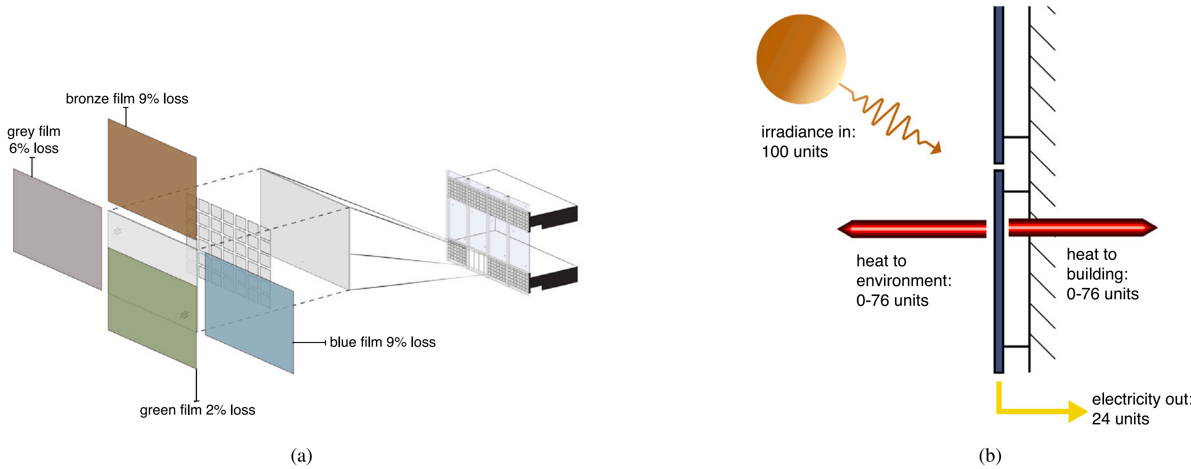


Fig. 13. (a) Potential options for semitransparent films that enable coloured PV modules. (b) The thermal relationship between BIPV facades and the exterior environment and building envelope is still an open question within the literature.

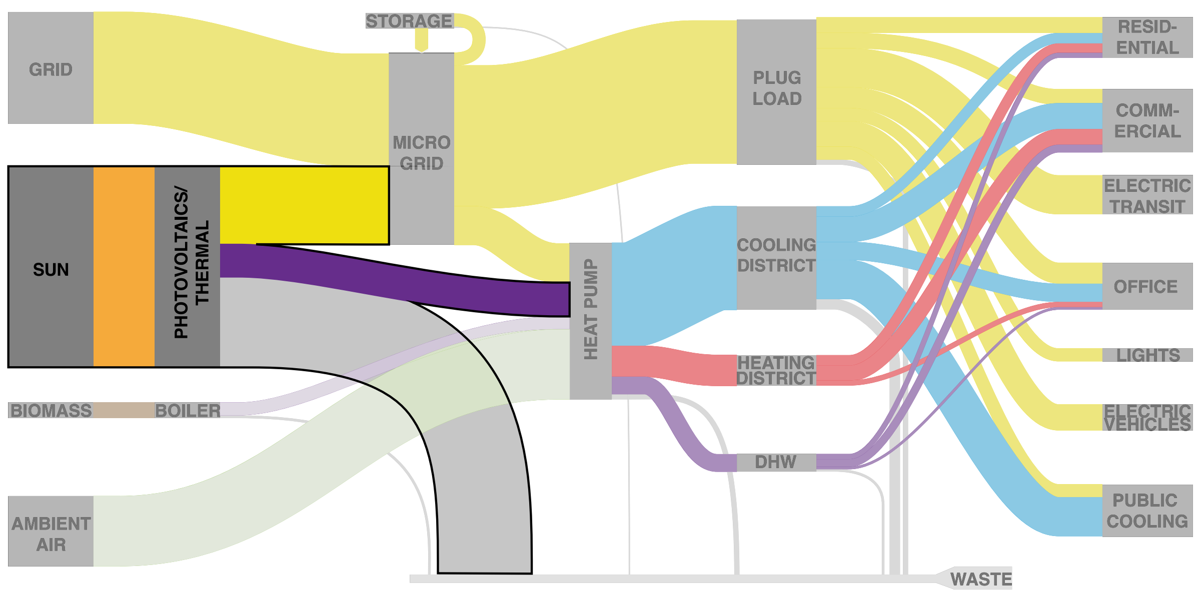


Fig. 14. A diagrammatic multi-energy system highlighting the flow of solar energy to photovoltaic generated electricity.

3. PCM-based research tends to show positive results but is often noted as being highly specific to the boundary conditions for the simulation or experiment.

The work found within this topic on UHI is conducted from an urban perspective with the open research questions on the subject holding clear implications for the deployment of PV systems in urban areas. Consensus has not formed on the impact of PV systems on UHI and vice-versa, but there is a clear impact in the literature reviewed with some variation in the general results based on location. Colour tuning and module manufacturing are studied mostly from a device and component scale, but their application is intended for BIPV and UPV. Similar to device level research in other topics the transfer of colour and module manufacturing research to the larger urban scale either for suitability stuides or uncertainty analysis was not found. Further research at the urban scale should consider the uncertainty present in manufacturing defects and the range of potential performance that different front cover treatments offer. PCM-based research is historically widespread in the corpus, similarly to BIPV/T research, but has not been transferred to the larger spatial scale.

3.8. Topic 8: Potential of integrated solar power to meet urban energy demand

The 36 publications reviewed from this topic focus on understanding the relationship between the electricity generated from integrated PV systems and the centres of electricity demand within the urban environment (e.g. electric vehicles or buildings). In Fig. 14 an example of how this type of energy system combining various energy sources, converters, and demand terminals might be constructed is shown.

Simulations of PV potential in urban areas are conducted in a majority of the publications and the outputs included within assessments of larger power systems. The scope of the simulations varies considerably ranging from country [244,245] and regional level analyses [246–249] to cities [250–252], then to districts and neighbourhoods [253–256] then to individual buildings [257–260], and then vehicles and vehicle networks [261–266], and lastly urban furniture [267,268]. Despite the varying levels of spatial assessment, the papers reviewed use similarly resolute levels of detail in their models and simulation. Most often the building geometry models are simply extruded footprints and yield prediction is done using performance-ratios and standard PV efficiency coefficients. The majority of the papers report on research focused on rooftops only, with only a few including facades and none focusing exclusively on facades. Several of the rooftop based studies are not looking into building rooftops, but those of vehicles or charging stations.

Several papers fall outside of this general category. Four papers report on the development not of PV cells or modules but rather supporting devices or infrastructure: solar-powered airlift pump [269], arduino-based net meter for grid connected PV [270], low-cost domestic scale PV data logger [271], internet-of-things smart metering for domestic energy management [272]. While a diverse collection of research, they speak to a theme within the research of smaller scale devices and the difference these face in integrating with large grids.

In four corpus members, the research looks at the relationship of PVs and the socioeconomic condition of communities: tying the an indicated need for more electric vehicle charging stations from surveys to the potential of distributed solar charging stations [273], exploring the historical trend societal shifts and energy transitions and projecting this to coming energy transition [274], reviewing employment potentials from the renewable sector in India [275], and reviewing survey results from residents in a sector of Ho Chi Minh City who overwhelmingly support small-scale residential PV deployment to reduce utility bills and enhance energy reliability [276]. These four papers present disparate results and themes but all tie into the recognition that PV presents a potential significant shift into urban energy consumption patterns.

One of the primary research agendas within the papers is that of balancing the electricity demand with the PV generation to maximise self-consumption within the energy system. Orioli et al. [253] discuss the importance of calculating the benefits of PV only from the electricity that is consumed on-site. Several pieces of research work within this concept by expanding the idea of the site to include multiple load centres in a district energy scheme [245,247,248,256,257,277]. A second agenda could be conducted with the need to understand when to apply different key performance indicators (KPIs) and forms of determining them. KPIs and their calculation methodologies are quite diverse within the corpus and two papers discuss different methods with no consensus forming on unified approaches [278,279].

The research in this topic explores the space of urban energy generation and urban energy demand.

1. Integration of PV into the grid is often studied from a modelling perspective at a large scale, with a trend towards multi-objective energy system optimisation. However, as indicated by roughly half of the content in this topic there are smaller scales to consider in the development of energy management devices and the impact of households.
2. Performance analysis is greatly influenced by the selection of a key performance indicators and when considering district energy, spatial scale and the construction of the load profiles.
3. When analysing PV performance at the level of a district or individual consumer it is important to consider self-consumed electricity separately from excess generation sent to the grid.

There are several distinct scales at play amongst the research covered by this review. In this topic a body of work dedicated to large urban energy systems can be found, whereas much of the previously reviewed topics were focused on component and small scale system questions. Again the review finds that these two scales are disconnected in that a majority of the papers do not specifically assess certain devices, but rather PV as a general energy generating concept. Future research should be sure to include a range of devices and deployment strategies to capture a larger range of performance. On the topic of evaluating performance, a large level of sensitivity in the techniques of analysis and evaluation of performance through key performance indicators was found indicating the importance of selecting task-appropriate key performance indicators.

3.9. Topic 9: Feasibility and impact of PV for sustainable energy generation in cities

Whereas the previous topic focused on PV as a means to address urban energy demand, particularly district energy demand, this topic contains more general research on building-based PV as a part of larger goals towards decarbonisation or sustainable development in urban design and architecture generally. It therefore contains publications that are not necessarily directly relevant to the urban scope of this review. Of the original 20 papers, two were removed for not being accessible, one for not being published in English, and five for not being relevant to either the urban scope or PV research.

In the remaining papers some form of building-based PV analysis is undertaken. The majority of the analyses take the form of financially-driven feasibility studies where the research is interested in understanding if rooftop PV can be implemented in their region and for their building type. The region is an important distinction in this topic as it informs the electricity price from the grid and the local excess PV generation tariff which are primary drivers of affordability. All financially-driven studies report that the tariff is too low or system costs are too high to make PV competitive with grid electricity [281–285]. When other factors are included such as energy payback [286], the stability of the grid [287], aesthetic appearance and value [280], or decarbonisation goals [288] the PV systems are viewed as beneficial. In Fig. 15 the increase in aesthetic integration with an existing rooftop impacts PV performance is depicted. In research of installed systems, two papers bring to attention several points on designing and planning systems. Stein et al. [289] report on the performance of several PV systems integrated into buildings in a military base in Arizona and report that maintenance is a primary factor in planning. Ikedi et al. [290] investigate data from an installed rooftop PV system and find that it does not perform as designed due to the expectations being based on nameplate capacity factors. One piece of research stands out as unique in the topic. Yoo et al. [291] correlate simulated BIPV generation to indoor daylight and develop a dimming controller based on the BIPV panels as a sensor.

Several findings are clear amongst the reviewed literature when assessing PV performance:

1. In financial assessment the grid price is a key influencing factor in PV performance.
2. PV was not financially competitive in the reviewed regions (Southeast Asia, the Gulf Countries) due to low electricity grid prices but remains attractive for visual benefit.
3. Maintenance should be considered early in the design stages for a system.
4. A performance gap may be seen if a system is designed based on standard test conditions.
5. Increasing self-consumption raises the financial viability of PV systems, particularly in regions where the solar tariff is low.

The findings from this collection of research largely speak to regional suitability of urban or building-based PV from a financial point of view towards the direction of facilitating a PV-based sustainable energy transition. While not a topic from an urban perspective, the findings do speak to the importance of well founded performance frameworks to ensure results that do not lead to increases in a phenomena known as the performance gap. Additionally, the range of results in terms of where PV is deemed suitable or not suitable speak to the importance of highly regionalised research strategies.

3.10. Topic 10: Empirical based approaches for successful integrated PV implementation

For this topic 44 publications were reviewed. They vary in scope, regional specificity, and methodologies but all revolve around the central theme of evaluating BIPV to understand best practices, barriers

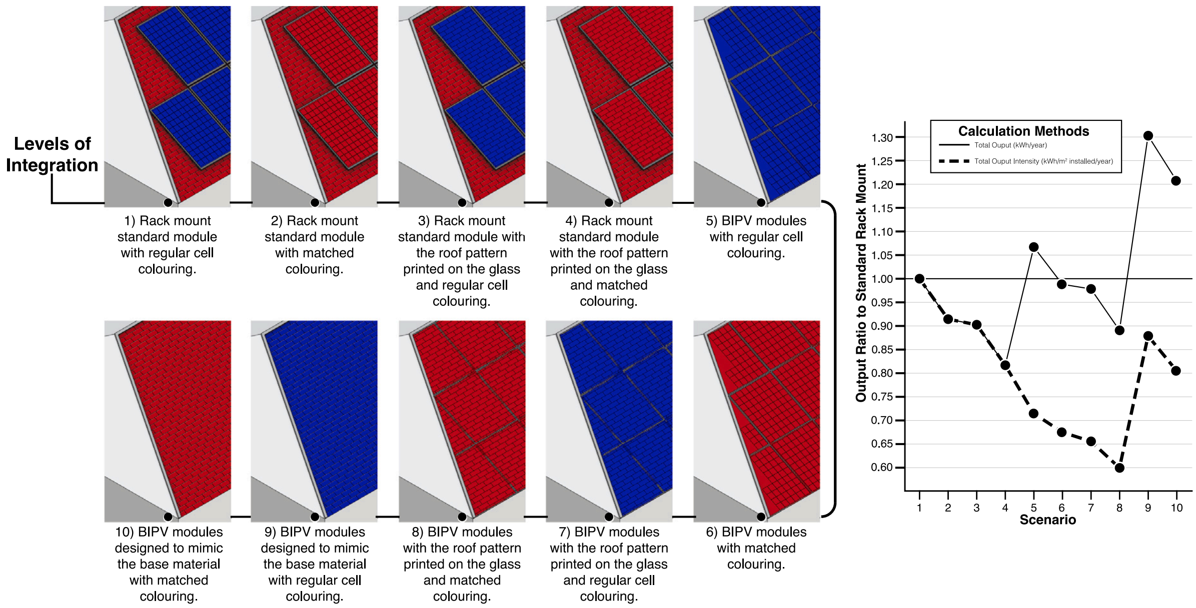


Fig. 15. The research of Hille et al. [280] is expanded to show increasing levels of aesthetic integration and relate the formulated array performance for each to a standard rooftop system.

to implementation, and general design parameters. The term "BIPV" can be found in nearly every paper beginning with Schoen et al. [292] where the research reports on an International Energy Agency task to study the potential to replace building components with PV modules. Two other reports predate this research with Ritschard [293] looking into the potential of solar electric power at a utility scale for American cities, and Knowles and Berry [294] describing the design studies that led to the development of solar cadastre zoning in Los Angeles.

Eight of the papers discuss some form a framework for evaluating BIPV utility. Two of these focus on aesthetics [295,296]. Four of these place their analysis of BIPV within the context of larger urban or architectural sustainability [297–300]. Bonomo et al. [301] and Hachem and Beckett [302] use some form of multi-criteria assessment frameworks. Sherko et al. [303] and Lau et al. [304] focus on the importance of building information modelling in providing a smoother integration process for BIPV to the construction phase.

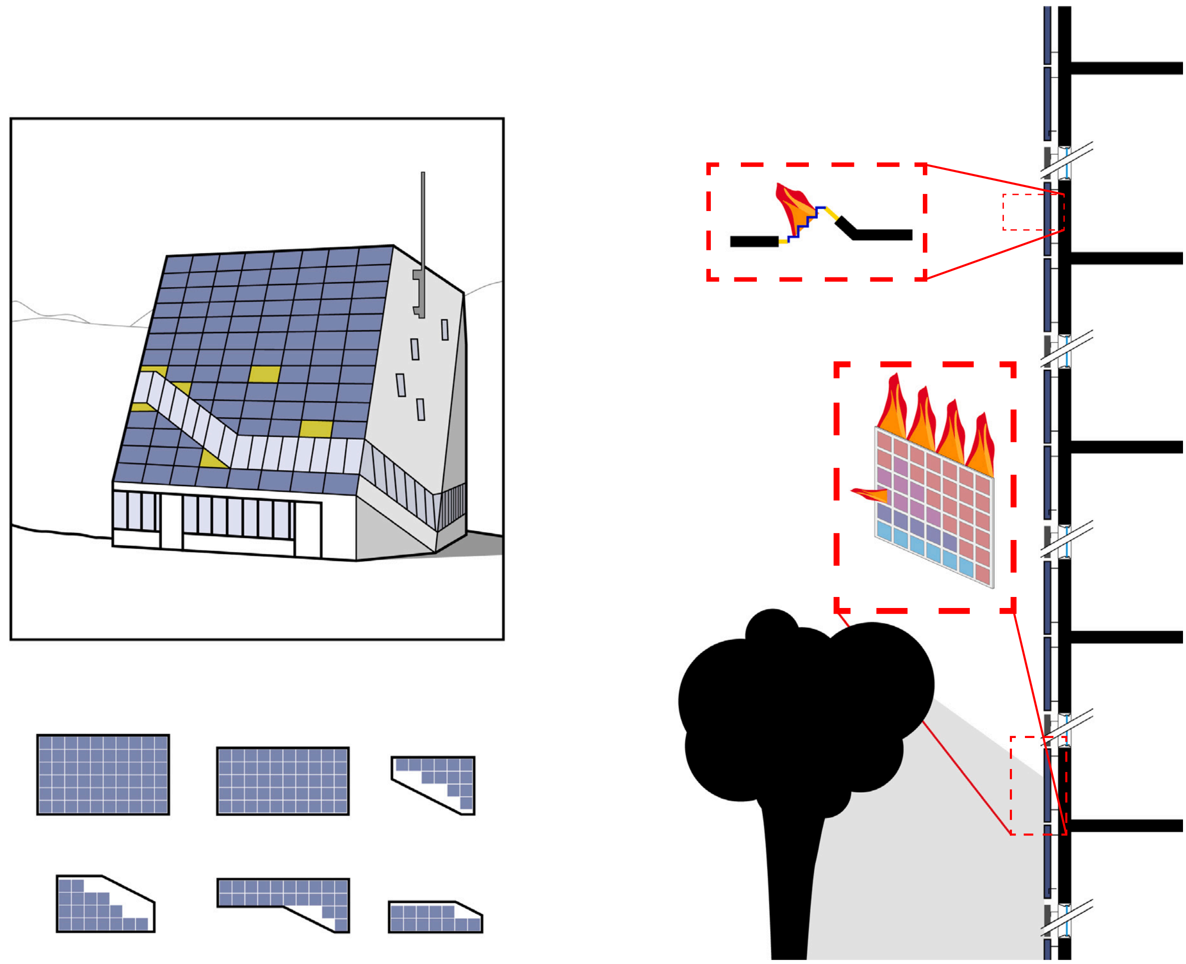
Four of the papers discuss life cycle concepts. Hammond et al. [305] and Bonomo et al. [301] incorporate life cycle impact analysis (LCIA) into their research. Brenner and Adamovic [306] and Mathur et al. [307] focus on the issue of decommissioned PV plants in Australia's Northern Territory and the lack of understanding and guidelines on how to recycle the modules. While not specifically urban or BIPV focused it provides a glimpse into potential issues facing the BIPV market in the coming decades as systems begin to age out of the warrantied lifetimes. While not focused on LCIA, several papers bring up the complexity of existing buildings specifically [308–310] and two papers discuss BIPV as a part of the larger urban development process [311,312].

There are two significant review papers which cover barriers facing BIPV generally [313] and the specific integration of PV into modular facade retrofit systems [314]. Both contain large lists of barriers ranging from the more commonly identified of high investment costs and lack of awareness to the more specific problems of a lack of international standards and commissioning protocols. Nine of the papers employ interview or survey based methods to understand the perception and qualitative aspects of BIPVs. This methodology allows the research to identify specific barriers to increased deployment of BIPVs. The cumulative results of these studies point to the high investment cost as being a primary barrier to both residential and commercial deployment.

Linked to this is the complexity of construction process which is of concern in five studies focused on this phase of the building process specifically [315–319]. Boyd and Schweber [319] identify that change orders in the construction process are due to a lack of contractor and installer involvement in the design of the building, where the designer of the system does not necessarily understand how it operates which leads to a widening of the performance gap in BIPV simulation. In addition to cost and complexity, the lack of awareness is identified as a third major barrier in four papers [320–323]. Lastly, in two papers the development of new module types are discussed [324,325]. This points to an interesting aspect of the BIPV research that differs from typical PV research which is often focused purely on the cell or the system. Integration requires a level of focus on the aesthetic and technical attributes of the PV device as it serves a visual purpose as much as a power generation purpose.

The research of this topic speaks to a wide range of barriers to BIPV implementation, which all can be related to buildings found in cities. Each of the barriers listed here, presents an avenue for future research within the UPV space:

1. The cost of capital prevents projects from moving past concept phase, despite advantageous returns on investment.
2. The segmented design and construction process is not set up for integrated products like PV that benefit from homogeneous form factors. See Fig. 16(a) for an understanding of where heterogeneity enters in BIPV design.
3. There is a lack of awareness in the profession to the existence of high quality integrated PV and how to design for it [326].
4. The temperature of surfaces (building and urban) is much higher when BIPV is present [327,328].
5. Existing buildings are more difficult to gain acceptance for due to existing aesthetic requirements [308–310].
6. There are shortages within the supply chain and labour market [329–331].
7. There is an information gap between research and practice [332].
8. The maintenance of the final array due to soiling is more costly and difficult than standard cladding [313,328].
9. There is not a policy alignment between different scales of government, which prevents effective incentives [333].
10. The risk of fire in BIPV products (shown in Fig. 16(b) is a barrier that is also met with policy confusion [313].



(a) (b)

Fig. 16. Two major barriers to BIPV implementation. (a) The number of unique modules used in the construction of the Monte Rosa Hut's BIPV system in Switzerland. (b) Potential fire risks associated with BIPV facades either through faults in wiring (top) or hot-spotting (bottom) from partial shading.

3.11. Mixed topics

The onus for this review is that UPV research is highly multi- and inter-disciplinary. In this group of publications the review finds a collection of work that is less singular in topical focus, at least from the viewpoint of the NLP methodology that was used for the review. Approximately 20% of the corpus members were not assigned a TAS of at least 0.5 to any of the topics ($n = 746$), with the distribution among different topics shown in Fig. 17. To concisely review this group of mixed topics sub-topics were developed from the most highly cited publications of the last four years. After the filtering of the larger collection for research published after 2019, leading to a reduction of 746 publications to 213 publications, 25 papers were selected. These 25 were selected from within the 90th percentile (six citations per year) of citation intensity, three of which were removed to irrelevance to UPV. From this group the remaining 22 papers were classified into five subtopics.

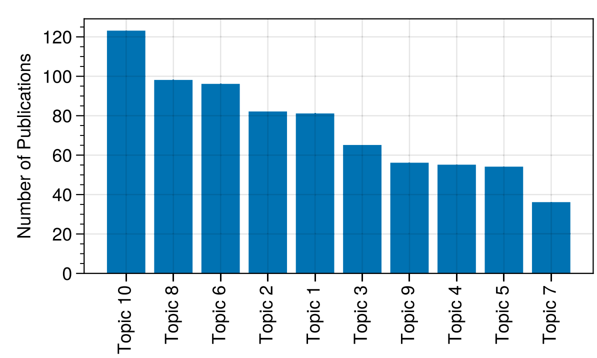


Fig. 17. Count of publications that fall into the Mixed Topics category from each of the prime topics.

3.11.1. Building design for optimal solar insolation

In the first subtopic the review finds research on the design of buildings to foster high levels of surface irradiance or improve PV system performance. Kirimtat et al. [334] review PV shading devices and their control systems and determine that more research is still needed on the integration of building controls and the actuation of PV shading devices. Cavadini and Cook [335] provide results for a parametric analysis of roof treatments, module temperature, and total yield. They conclude that cool roof designs provide a larger benefit to rooftop arrays through the reduction of temperature, but note their results should be considered regionally specific. Poon et al. [336] conduct a parametric analysis of the influence of varying building morphology indicators on the irradiance of urban rooftops and facades in Singapore. They show that rooftops irradiance intensity [$\frac{\text{kWh}}{\text{sqm.}}$] varies little with the factors. However facade irradiance is highly susceptible to sky view factor and sky exposure fact, which are computationally difficult to acquire without building geometry information. They develop a multi-linear regression model based on more common geometric descriptors to supplement missing 3D information. As discussed in Section 1 Sailor et al. [9] review PV in urban environments, but specifically to this subtopic they propose future research should focus on the design of modules that can reflect portions of the solar spectrum that are not useful for the solar cell in order to reduce heat gain.

3.11.2. PV as part of a system

In the second subtopic the research is focused on reporting the results of specific case study analyses that are either focused on PV performance or incorporate PV into a larger systems. Three provide the results of a power analysis for a proposed city and find that PV (if optimised) can meet a moderate (20%–40%) amount of the electrical demand [337–339]. Lastly, during an assessment of a large-scale PV plant for an airport Sreenath et al. [340] note the importance of glare assessment for larger ground mount arrays near population centres and airports.

3.11.3. Defects in next-generation solar cells

The third subtopic contains two publications on cell science, both focusing on improving the defect rate on perovskite solar cells. Ono et al. [341] provide a comprehensive review of the defects and note that the literature does not yet provide an understanding of the nature of defects in metal halide perovskites at the scale necessary to comprehensively overcome the challenges faced. Ling et al. [342] report on the development and fabrication of a film layer for a lead iodide perovskite solar cell, reducing defect density without detrimental impact on the final device conversion efficiency. It is curious that these do not register primarily with Topic 5, which contains perovskites. This can be attributed to the use of certain keywords that are typically found in other topics, such as the word "film" which is found in both paper abstracts but used differently that where it is more commonly found in Topic 4.

3.11.4. PV device design and engineering

The fourth subtopic is focused on the design of cells, modules, or arrays. Three are focused on surface coating and texturing for modules and cells. Kim et al. [343] provide a review of cell texturing at the nano- and micro-scale to improve cell efficiency noting that many techniques reviewed have entered into commercial use. Riedel et al. [344] and Royset et al. [345] provide separate assessments of coloured treatments for cell aesthetics. Their findings appear to disagree on the influence of a greenish colouration with the former noting that green outperforms that other treatments, while the latter note that green provides the largest reduction in power output. While not focused on surface treatments, the review from Borrebaek et al. [346] on techniques to avoid snow and ice accumulation on BIPV facades determines that in addition to application-specific solutions, hydrophobic surface coatings have shown to be effective. Pillai et al. [347] describe a novel technique for rearranging strings of PV modules in an array to improve their performance during partial shading which brings about between a 2%–16% improvement depending on the stringing scheme being compared to; Dominance Square being the best scheme otherwise. Kant et al. [348] report on the use of nanoparticles to enhance the performance of PCM's, finding Copper is the best additive. The last paper was mentioned in Section 1, [8]. There the research reviews design options and taxonomies for BIPV, stating also that more demonstration is necessary along with more connection of research and practice.

3.11.5. Country to global scale assessments of BIPV viability

The fifth subtopic is comprised of five papers that are focused on large scale assessments of PV viability. Gholami and Røstvik [349] provide a life cycle cost analysis of BIPV as an envelope material and frame their analysis through multiple European countries. Their results indicate that discount rate is influential on the financial viability of the system and that if social and environmental costs are included in a life cycle cost analysis evaluation of BIPV then all but the northern facade can be considered a profitable host of BIPV in most of Europe. Alkhayat and Mehmood [350] review forecasting methods for PV that are based on deep learning. They find that hybrid approaches (combined deep learning methods) and Recurrent Neural Networks are the most common and that most papers report high levels of accuracy. However, they note that most approaches and their accuracy are likely regionally specific and implementing the model would require retraining for context. Joshi et al. [351] conduct a global assessment of rooftop PV potential using remote sensing and evGeographic Information Systems-based techniques. They note that their approach is limited by the level of resolution but conclude that only 50% of the world's rooftop capacity would need to be accessed to cover the aggregated electricity demand of the entire world, if storage is available. Sward et al. [352] critique evGeographic Information Systems-based assessments of PV plant suitability based on the lack of inclusion of social values. They state that while these multi-criteria-decision analysis frameworks are effective for financially viable utility scale plants they should be combined with social surveys. Lastly, Zhang et al. [353] use household energy data from each of China's provinces to assess the viability of distributed solar energy as a decarbonisation and development tactic. They found that for electricity demand, at present, it is viable but in cold climates a supplement for heating is needed.

3.12. Topic analysis summary

The topic modelling review identified ten core research areas, each offering an understanding of the current state of research in the field. The first five topics presented (T1-T5) explore computational and technical aspects of irradiance modelling, simulation accuracy, partial shading, PV technology development, and third-generation solar cells. Studies in surface irradiance modelling (T1) examine how to accurately model the shading effects of urban elements like vegetation and street furniture, and how to speed up computational simulations. Meanwhile, PV system modelling (T2) identifies a nascent field still relying on lower resolution methods to reduce computational complexity, but often lacking consistency in methodologies across different scales or regions. Partial shading effects and research on electrical mismatch (T3) show that the heterogeneous surface insolation conditions in urban environment pose a major concern for PV productivity, with varying results indicating the need for standardised shading conditions to improve research consistency. Advanced PV technologies (T4) and third-generation cells (T5), focus on next-generation materials like LSCs and perovskite solar cells, which, despite offering unique advantages for urban integration, are still somewhat isolated from larger-scale urban research as they are considered long-term for urban deployment strategies due to durability concerns as well as commercial availability. We note that the identification of two separate topics on cell and module technology is important as the UPV field should contend with emerging technologies.

The latter five topics (T6-T10) expand on broader considerations for UPV deployment, ranging from understanding how to utilise or reduce waste heat in PV arrays (T6) to the interplay between UHI and PV performance (T7). The literature on excess heat reveals that much of the knowledge is derived from larger, non-urban systems, calling into question its direct applicability to city environments. Urban energy systems research (T8) shows that most assessments focus on large-scale energy systems without directly addressing the nuances of individual devices or deployment strategies, highlighting the need for more fine-tuned analysis at the device level. Regional suitability assessments (T9) stress the importance of local conditions when determining the viability of UPV systems. This section included several case studies, noting that regional specificity in research methods is crucial to avoid generalised conclusions that could exacerbate the UPV performance gap as well as to inform policy development. Finally, barriers to BIPV implementation

(T10) highlight a wide range of issues, from financial constraints and supply chain shortages to design complexities and the misalignment of regulatory standards and policy.

Lastly, a set of mixed-topic publications was identified through the difficulty of the topic model to discretely label around 20% of the corpus members. However, reviewing the highly-cited research within this group provided further insights into the outlay of the UPV domain as well as contemporary research topics. For example, the research on optimising buildings for irradiance highlights the importance of parametric analysis in optimising roof treatments and morphology for better irradiance, but points to region-specific considerations that complicate generalised models. Case studies focused on PV as a segment of larger energy systems reveal that, when optimised, PV can meet a substantial portion of energy demand in urban areas, though attention to factors like glare is essential in densely populated areas. Publications on the shortcomings of next-generation solar cells emphasise the need for better understanding of defect mechanisms in perovskite solar cells. This connection is crucial to understand at the scale of urban research as advancements in material science could play a critical role in future urban PV deployment. Meanwhile, PV device design and engineering studies showcase a range of solutions to improve module aesthetics, shading performance, and durability, though inconsistencies remain across the literature regarding the best design approaches. Finally, research on regional and global BIPV performance and viability demonstrate that the financial and technical feasibility of BIPV varies significantly by region, underscoring the need for research to be localised.

In summary, this data-driven review organised the UPV literature into ten topics. This provided an overview of the current research landscape and the review was able to identify opportunities for future research. Given the limitations of the data-driven approach, which are discussed later in Section 5, a manual distillation of these insights was deemed necessary. Therefore, the research landscape was further organised into six targeted research agendas, presented throughout Section 4. This additional analysis is aimed at guiding future work in UPV including the importance of working across scales and disciplines, keeping up with technical advancement, and focusing on regional specificity in shaping the future of solar energy in urban environments.

4. Discussion

The data driven review process led to the creation and summarisation of ten topics and an additional grouping of publications under mixed topic classification. As detailed later in Section 5, there are limitations to this approach as the LDA, and NLP generally. The data-driven process may not accurately classify all text tightly, which was evident in the mixed topic analysis. Therefore the topics themselves and the research from each topic was reviewed and the following thematic areas were developed. In the following subsections these manually developed, which may be thought of as potential research agendas, are described generally. Additionally we point towards the research gaps for each of the six areas. Additional research was included to provide a more holistic view of the field, ensuring that the resulting agendas were both well-rounded and forward-looking. The research gaps are described below in the four thematic areas that were synthesised from the ten topics: (1) relationships between different scales of research or the lack thereof (Section 4.1), (2) the standardisation of analytical approaches (Section 4.2), (3) the trends in regionally specific research and its importance to the selection of effective systems (Section 4.3), and (4) UPV and its relationship to heat in the urban environment (Section 4.4). Following the introduction of the thematic areas several research trends are discussed that emerged throughout the review process, but were not apparent in the latent topics (Section 4.5).

4.1. Scalar relationships

This research discusses this in more detail as well as how looking at the technology at a finer scale may impact uncertainty in urban scale analysis. In keeping with a later discussion point on the standardisation of analytical approaches this research also reports the findings on different scalar approaches to modelling an simulation.

The identified research spans a range of scales, from the development of novel PV materials to the integration of UPV systems in urban energy districts. Despite this diversity, most studies focus on specific spatial scales without addressing how advancements at one scale—such as material improvements—might influence a separate scale-such as UPV deployment pathways. Research that moves across this gap would allow for more comprehensive insights into how different PV technologies could be optimised for urban environments. Furthermore, large-scale UPV studies often simplify the characteristics of different technologies. This can obscure nuances in performance and lead to underestimations of uncertainty, as well as enable a research regime in which advancements are ignored through continuous references of the same technology standard. These subthemes explore how multi-scalar frameworks, incorporating technology-specific traits, can be developed to address these challenges in urban deployment.

The first subtheme (Section 4.1.1) highlights the disconnect between PV material innovations and their application at the building or urban scale. While research on PV materials such as OSC and PSC demonstrates diverse and substantial performance improvements, few studies translate these advancements into system-wide deployment models for cities. Current urban-scale studies often treat PV as a single, generic material, overlooking how specific material characteristics could optimise performance for different urban use-cases, as well as the lifetime impact related consequences of different materials. A comparative approach, applying simulation or experimental analyses across multiple urban scenarios, could reveal how different PV technologies might be strategically deployed to enhance urban energy systems.

The second subtheme (Section 4.1.2) examines the importance of aligning simulation methods with spatial and temporal scales appropriate to UPV. Methodological consistency is essential for a larger reliable field of study, yet many studies apply techniques across scales without fully justifying their appropriateness. More detailed models, such as ray-tracing for partial shading or current–voltage curve analysis, are useful at finer scales where shading is a concern but may be computationally excessive at broader scales. Multi-scalar frameworks could help define which methods and data inputs are optimal for specific urban contexts, improving the comparability and accuracy of UPV studies.

In a connection to the second subtheme, the third (Section 4.1.3) addresses the complexities of predicting UPV system performance at the large scale. UPV deployment introduces a variety of risks, including degradation, installation factors, environmental impacts like soiling, and partial shading, that can significantly affect performance. Existing studies rarely account for these uncertainties in their models, leading to potential discrepancies in projected versus actual energy output. Developing a framework for incorporating different types of loss associated with urban elements in large-scale deployment studies would provide a more reliable basis for UPV planning, particularly when assessing the long-term viability of systems in dense urban areas.

4.1.1. Applied technology development research across scales

UPV systems can be considered to be made up of multiple components for which various possible alternatives exist and can be developed to operate at a variety of scales (e.g. small transit-station canopy, building rooftop or facade, district energy base-loads) and for different purposes (e.g. rain screen, skylight, double-skin facade). The relationship between the fundamental properties of different PV materials and these purposes is understood in the research written about the materials and the development of new technologies, seen in Topics 3.3, 3.4, and 3.5. However, the subject of material sensitivity has yet to be written about from the perspective of urban-scale system design, with the exception of several studies related to social perceptions discussed later. Often research into BIPV or UPV integration into district energy schemes relies on a simplification of PV to a generic material or conversion efficiency. However, as noted in Fig. 10, even in a small portion of PV materials there is a wide range of performance to be found. Therefore, there is a gap in relating the specific properties of different PV materials to their potential use-cases in urban environments. In [8,354] the authors review provide comprehensive analysis of different PV technologies and emphasise their performance, as well as the challenges for integrating them in urban settings. They highlight the importance of selecting appropriate technologies based on specific urban conditions and the potential for emerging technologies to offer innovative solutions. A comparative analysis of different PV technologies should be conducted using simulation or experimental methods in different urban settings to provide researchers and practitioners with and understanding of the relationship between technology traits and urban characteristics.

The performance of solar cells is also expected to improve over time [326]. While there are not many large-scale studies in the reviewed literature that focus on multi-stage deployment, this research notes that those that were found in the review do include some parameter to reflect this [355]. However, it is important to consider that while PV technology performance is expected to increase other technologies which PV may be evaluated against as feasible will likely also experience change. Therefore future research should take a comprehensive view of the future energy technology landscape such as in [356].

4.1.2. Scalar approaches to modelling and simulation

At the forefront of many topics is the discussion of methodological frameworks for irradiance estimation as well as UPV power calculations. Methods applied within each topic vary with little justification to their specific use. Additionally, similar methods can be seen across scales such as remote sensing used for irradiance estimation for building specific questions as well as assessments of PV viability completed for the entire planet. Coupled to this question of irradiance estimate is that it may be prudent to use more detailed models for irradiance (e.g. ray-tracing) and electrical output (e.g. current–voltage curve based analysis) where the risk of partial shading is present [357]. Models such as those proposed by Waibel et al. [358] allow for computationally efficient irradiance simulations that can take into account common urban obstructions such as vegetation and if coupled to the electricity generation simulation provide more accurate results of loss due to partial shading. However, it may not be necessary to use such detailed approaches when looking at large areas or many surfaces, as shown in the comparative analysis of simulation frameworks from the authors [359]. This multi-scalar approach can be used in large-scale assessments of deployment as well as in simulation. Kapsalis et al. [360] first take a GIS-based approach for a global review of rooftop PV. This is coupled to a deeper analysis of the impact rooftop PV on building physics in different regions. The findings underscore the differences in PV deployment and operation in different climates through an analysis that spans two scales. Lastly, Tian et al. [361] provide an overview of machine and deep learning approaches for forecasting both solar radiation and PV yield in cities. Their review is separated into spatial groups, with micro-scale and building-scale research being relevant to the present research task. However, they note that research at this scale is still small compared to larger scales and more opportunities exist for developing methodologies. Their review indicates that methodologies in the UPV space are trending towards machine learning approaches due to their emerging robustness and computational efficiency, but it is clear that smaller scale work spread across large areas is still underdeveloped. Therefore future research should focus on defining at what scales and in which contexts different methods and input datasets should be applied to improve comparability between research outputs in the urban domain.

4.1.3. Uncertainty in urban scale deployment analysis

Discussion about monitoring the evolution of technology when conducting urban scale feasibility analysis uncovered another factor concerning technology and large-scale analysis; uncertainty in technology operation and evolution timelines. This research found in Section 3.3 that there is potential for systems to experience a range of performance related problems that may impact research findings. These include performance reduction over time, cease to operate due to internal failures or external factors such as hail, suffer from soiling, or they may be installed in a non-optimal manner. Future research should focus on developing a framework for uncertainty analysis in deployment studies for UPV, particularly when the research is focused on large scale deployments.

4.2. Standardisation of analysis

Standardised frameworks and methodologies are essential to ensuring reliable and comparable results across studies in any field of study. This section outlines two primary research trends that emphasise this need: establishing consistent analytical approaches and the integration of LCA to provide a comprehensive view of UPV's environmental impact. Together, these themes highlight both the technical challenges of aligning diverse methodologies and the necessity of adopting holistic evaluation frameworks for a sustainable urban PV landscape. The following sections expand on the following subthemes, examining how methodological consistency and lifecycle thinking can drive the field of UPV research towards greater sustainability and alignment.

The first subtheme (Section 4.2.1) addresses the challenge of comparability within UPV research. Current studies vary widely in their use of metrics, units, and temporal resolutions (e.g. hour vs. month to calculate self consumption), with different functional units (e.g. $\mathrm{kWh/yr}$, $\mathrm{kWh/sqm}$, $\mathrm{kWh/kWp}$) applied to report performance. This inconsistency complicates efforts to draw reliable comparisons across studies. Additionally, discrepancies in simulation tools and their handling of factors like partial shading further contribute to variability. Establishing unified performance metrics and improving simulation reliability would enhance the comparability of research outputs and enable more accurate assessments of UPV potential

The second subtheme (Section 4.2.2) underlines the importance of evaluating UPV systems from a lifecycle perspective to prevent the deployment of systems with a negative net impact. While operational phases of UPV are often considered carbon-neutral, few studies address the environmental impacts associated with manufacturing, installation, and end-of-life processes, however this has increased in recent years. LCA provides a framework to capture these embodied impacts, allowing researchers to assess the net environmental benefits of UPV systems comprehensively. Future research should incorporate parametric LCA approaches from the early design phases, supporting sustainable urban planning and enhancing the understanding of UPV's long-term impact.

4.2.1. Standardisation of analytical approaches

Among the research reviewed various functional units used to communicate research results as well as define performance were found. This is reasonable as different research questions may require different functional units to report specific KPIs. However, it makes comparison between research outputs difficult. This is apparent in reporting output from systems different functional units are used which are hard to compare: $\frac{\mathrm{kWh}}{\mathrm{yr}}$, $\frac{\mathrm{kWh}}{\mathrm{sqm}}$, $\frac{\mathrm{kWh}}{\mathrm{kWp}}$. The former can be useful in comparing research if the installed sqm or kWp are known. The latter two can be useful if the underlying sqm or installed $\frac{\mathrm{kWp}}{\mathrm{sqm}}$ are reported in the research. Similar to the earlier point about the standardisation of simulation frameworks for different scales of analysis, the standardisation of data reporting would enhance the comparison between different work, as would standardising a set of types of system performance. For example in studies that look into BIPV through mutli-objective optimisation where financial cost and carbon-mitigation potential are viewed in opposition due to the relatively high capital cost of PV when compared with conventional electricity generating systems. However, if choosing to view performance from a carbon emissions perspective, PV can perform better. Furthermore, as shown in Fig. 7(a) the incorrect temporal resolution of an analysis can lead to drastically different results from an experiment, an output echoed in the research [77]. Looking beyond functional units to the manner in which they are produced there are a wide variety of tools and approaches for simulating PV yield in urban conditions. In a comparison of simulation tools of BIPV assessment, Jing Yang et al. [362] found that the range of simulation relative difference of yield from the tools' simulations to measured yield ranged between −5% and 8% for rooftop systems, −1% and 26% for facade systems, and −6% to 11% for canopy systems. This is in part due to differences in how the tools handle electrical mismatch from partial shading. Their suggestion is for a focus on improving equivalent sicurit model access within common PV tools.

4.2.2. Life cycle analysis in UPV

Regarding the analytical framework used to assess simulated or measured data and begin to frame optimal performance metrics there is a lack of LCA within the assessed corpus materials, with the exception of a several examples [305–307,363]. LCA is key to accurately characterising the performance of a UPV system from the perspective of the net-environmental benefit that the system will provide from its manufacturing to its end of life. While operationally a UPV system is low or even zero carbon from an emissions perspective, there are initial emissions associated with its creation. Given the potentially high upfront emissions in terms of greenhouse gas (GHG) emissions outweighing the potential mitigation potential of a proposed PV system this research notes that it is important to consider a variety of indicators when discussing UPV viability. Future research should therefore include life cycle thinking and be aware of its inherent challenges [364]. Furthermore parametric LCA should be applied in early design stages to enable planners and architects to design a more sustainable built environment [365].

4.3. Regional research trends

PV, being highly influenced by the sun's position, is highly contextual to location-specific factors. The growing body of UPV literature has brought attention to several critical areas where performance standards, deployment strategies, and location-specific conditions influence the suitability of PV. In this thematic area, regionally-specific research is the focus. In the following sections two central research trends that define the current landscape are discussed: the need to identify and standardise performance thresholds for UPV and the importance of addressing location-specific barriers. These themes highlight both technical and contextual challenges, emphasising that while some standards may be broadly applicable, others require fine-tuning to fit local conditions and architectural styles. The following sections delve deeper into these challenges, reviewing key studies that uncover the intricacies of performance thresholds and location-specific deployment issues in UPV research.

The first subtheme (Section 4.3.1) focuses on defining measurable standards and performance benchmarks that can guide PV integration at different scales. Surface irradiance thresholds illustrate how simplified metrics can streamline PV analysis across urban districts by screening out suboptimal surfaces. However, evolving technologies and location-specific conditions suggest that new, context-driven thresholds are needed. Recent studies have connected irradiance thresholds to LCIA, which opens new pathways for setting local performance targets and material development goals.

In contrast, the second subtheme (Section 4.3.2) highlights the complex localised challenges that affect UPV deployment, from aesthetic preferences to urban shading. Research shows that socioeconomic factors, climatic variations, and architectural norms all play a role in shaping PV suitability at a regional scale. Technical issues such as partial shading in dense urban areas and the variability in urban heat impacts underscore the need for tailored solutions that align with specific city planning paradigms and climatic conditions. Addressing these barriers will likely require both locally adaptive approaches and the establishment of global standards, ensuring that while PV systems are customised for regional use, they also meet consistent performance and safety benchmarks.

4.3.1. Uncovering performance thresholds

As this research first described in Section 3.2 Compagnon [93] describes a useful metric for simplifying solar PV analysis in urban environments, the surface irradiance threshold ($\frac{\mathrm{kWh}}{\mathrm{sqm}}$). The threshold describes the annual amount of irradiance available to a surface and can be useful for removing less optimal surfaces from analysis in order to reduce complexity during large scale urban energy planning. The evaluation in the paper was that $800\frac{\mathrm{kWh}}{\mathrm{sqm}}$ was an acceptable threshold for facade-based systems and this value can be found throughout the reviewed literature, despite changes in the technology potentials with time and with the change in context per analysed location. The original publication additionally reference their threshold value of $800\frac{\mathrm{kWh}}{\mathrm{sqm}}$ as being aligned with a similar rule that was based on using 80% of the maximum annual irradiation for a location. While location specific and likely misapplied in many works the concept nonetheless has inherent value as a metric to reduce analysis complexity at a high level. It is therefore recommend that future work focus on the discovery of context-driven threshold values such as in Happle et al. [366] where, in the research, the irradiance threshold is connected to lifecycle carbon emissions intensity of UPV systems, comparing it to local electricity grid mixes.

From another perspective this research can identify in some publications regarding optimal PV deployment in cities there are thresholds of performance that materials must meet before they can be considered to be a part of an optimally designed district energy system [355,356]. This type of finding can be used to establish technology development targets at a material scale or provide thresholds for LCIA-related performance that devices must meet before they can become regionally useful.

4.3.2. Location specific barriers

The research on deployment barriers related to UPV is often presented as universal with little discussion of location specific barriers or solutions. This research proposes that future research into the barriers facing UPV deployment should be addressed from the perspective of the local context. For instance, Sailor et al. [9] note that literature is divided on a key question surrounding UPV, the impact of integrated modules on the urban heat environment. In their review they discuss the regional differences found in the literature. Their review also lists major technical barriers to optimal PV performance in urban areas. Partial shading, which was reviewed in Section 3.3, is a primary challenge to enabling UPV to achieve the same levels of performance seen in GPV. While policy and planning paradigms such as those presented by Knowles [367] might prevent urban development from shadowing already installed PV systems, it does not deal directly with small shading events. These solutions are much more specific to the site and are complex to model. Therefore future research should include a methodological input for reducing the complexity of partial shading objects on modules. Other location specific barriers include those related to aesthetics, such as the survey-based approach from Hille et al. [280]. While global consensus on BIPV aesthetics tend to revolve around masking the appearance of the raw solar cell, there are examples of projects that manage the appearance of the solar cells as a larger part of the architectural integration. Therefore, this research encourages future research into barriers around aesthetic preference to be completed with regard to regional or local architectural and urban characteristics. This is due to the highly specific nature of socio-economic issues relative to their locale, which makes them difficult to model or generalise as noted in [354]. Lastly, as PV yield is highly tied to irradiance and other meteorological traits of a site, it is key to place research in local climate contexts [360]. However, it is important to recognise the importance of a global approach to the development of testing and standards, as Bonomo et al. [368] uncover in their review of the state of BIPV deployment. Despite this, a regional focus should not be lost as Skandalos et al. [369] note in their climate-based analysis of BIPV. that in addition to the differences in yield and how this connects to the influence of a local climate on building energy use, BIPV elements are also used as weatherproofing which entails another level of regional specificity.

4.4. Urban photovoltaics and heat

Heat dissipation and management in the built environment is a primary focus for much of the research as climate change and higher density development exacerbates the issue of urban heat [370]. This section explores three key challenges in UPV heat management that emerged from the literature: the need for accurate temperature models for integrated PV systems, approaches for addressing waste heat generated by UPV systems, and the coupled interaction of UPV and the urban microclimate. Together, these topics underscore the technical and environmental complexities that arise when deploying UPV systems.

The first subtheme (Section 4.4.1) addresses temperature models calibrated for UPV, particularly BIPV installations. Most existing empirically-derived models rely on data from GPV systems, which do not account for the unique boundary conditions of integrated installations. These generic models can misrepresent the operating temperature of an integrated system, complicating suitability assessment. Future research should focus on developing validated temperature models tailored to integrated PV systems.

The second subtheme (Section 4.4.2) considers the challenges of managing unwanted heat within urban environments as it is related to PV generators. Excess heat can reduce PV efficiency, increase thermal loads on building envelopes, and potentially exacerbate UHI. The literature reviewed points to strategies like BIPV/T systems as a solution. Despite the technical potential of BIPV/T to enhance heat dissipation and improve system performance, these technologies have yet to reach commercial viability. Additional research is needed to address the barriers to market adoption, focusing on advancements that improve BIPV/T feasibility and optimise UPV systems for low-temperature operation.

The third subtheme (Section 4.4.3) explores the bidirectional relationship between UPV systems and urban microclimates. While UPV can contribute to localised heating effects, microclimatic conditions also impact UPV performance, with shading, ventilation, and ambient temperature playing crucial roles. Sailor et al. [9] review these interactions, noting that despite promising findings, the effects of UPV on microclimate are not yet fully understood. Further research is required to clarify these dynamics.

4.4.1. Model for integrated PV temperature

UPV has developed as a focal point for PV material scientists, electrical engineers, and urban scientists over the past decade. The speed with which interest has developed has meant the adoption of techniques and models from the GPV domain for urban contexts. One example where a known research gap is present is in the use of existing models to characterise back of module temperatures for integrated arrays. Developing a domain-specific set of models to characterise different types of UPV devices is essential to accurate modelling. Furthermore, as fire-safety becomes a focal point within the industry being able to simulate integrated array temperature with a validated model is key to overcoming regulatory hurdles. Future research should focus on a back-of-cell or back-of-module temperature model for integrated PV systems of varying types that is similarly useful as such models as the Faiman temperature model [175].

4.4.2. Excess heat in UPV systems

While the existence of undesirable heat in a building or urban environment is not necessarily a new occurrence due to deployment of a UPV system, it does still require management. This has led to the conceptualisation of dual systems such as BIPV/T as seen in Fig. 12 and a focus on reducing the operating temperature of devices to improve conversion efficiency as seen in Fig. 11. While a large quantity of literature on BIPV/T is available, the technology has yet to make its way to the market. Future research should be focused on understanding what advancements are necessary to make BIPV/T a market-ready technology. Furthermore designing integrated PV systems to operate at lower temperatures should be a focus going forward. Therefore, developing a similar catalog to that shown in Fig. 14 for simply reducing the amount of heat stored in integrated PV cavities should also be a focus for future research.

4.4.3. Microclimate interactions with UPV

Sailor et al. [9] review research on the relationship of PV and the urban microclimate, both the impact of the microclimate on the performance of PV and the impact that PV has on the microclimate. Despite their review and the research mentioned in Section 3.7 there is still a need to pursue a deeper understanding of the interactions. Their review serves as the most up-to-date overview of the subject and uncovers division within the literature surrounding questions of UPV and heat. Furthermore they stress that despite the promise of the technology as a low-carbon and renewable energy source, future research should be careful in how they convey the benefits of the system and be sure to depict accurately the microclimate interactions.

4.5. Additional research trends

As is discussed in Section 5.4, the initial search terms used to build the corpus create a situation in which several research trends known to be relevant to UPV are overlooked. While an exhaustive list and investigation of all relevant literature to UPV is not possible, several notable trends that were uncovered in snowball-type research exploration and throughout the review process of the paper are included here. It was found that these trends are emerging within the UPV field either due to their general newness, such as non-building based PV systems in cities, or as a extension of research from GPV-based research, such as with bifacial solar modules.

4.5.1. Urban energy districts

PV can be applied in newly planned urban energy districts to improve carbon emissions abatement. This is a well established practice, particular using rooftops. Urban energy districts offer a pathway for communities to coordinate their own energy supply for any one of several objectives (e.g. carbon emissions, cost, resiliency). Typically this takes the form of thermal distribution networks which must be spatially contiguous. Deploying PV and storage systems at the same time can help enhance the efficacy of the system in meeting customer loads [371]. Emerging research suggests that PV can also be applied in non-spatially contiguous forms through the use of virtual power plants [372,373]. However, this research has yet to take on an-urban specific theme, focusing more on suburban style residential dwellings. Lastly, an established research trend is that of load matching for UPV design. In this practice, load demand profiles are studied and azimuth and tilt optimisation is undertaken to fix generation capacity in place from a temporal suitable perspective, mitigating the need for storage [374].

4.5.2. Bifacial cells

The increased energy output per surface area used of bifacial cells has been identified as beneficial to UPV cases, particularly BIPV [375]. This emerging area of research is responsible for understanding how best to implement this new technology in buildings and other urban spaces; in essence taking advantage of reflected solar radiation. Several cases suggest that given the correct application bifacial modules can provide a nontrivial amount of additional electricity in facade applications [376,377]. Furthermore, the combination of this technology with other UPV deployment cases is beneficial, such as in noise barriers [378].

4.5.3. Urban specific degradation of PV

As noted throughout the review, the operation of PV devices in urban areas will include a set of boundary conditions that is different from those seen in the majority of PV deployment cases (i.e. GPV). Not only will the heterogeneous irradiance and temperature conditions of the modules in UPV cases impact system efficiency, they will also impact a PV device's lifetime. Due to the wider nascency of systems like facade BIPV, the observational study of the impacts and comparison to GPV is difficult. However, there is experimental research suggesting that certain events such as dust storms impacts PV differently in cities than in GPV cases [379]. Additionally, the collection of research surrounding degradation points to the need to specifically understand different regions, climates, and PV technologies as they interact differently [380,381].

4.5.4. Non-building based UPV

The predominance of literature relation to building-based PV is in part due to the search terms employed. However, it is also generally more common to see PV deployed on building surfaces rather than in other forms of deployment such as covering open parking lots [382], atop utility poles [383,384]. The corpus contained several studies on non-building based PV, but these were largely restricted to specific cases and often relevant for transportation [261,385]. Lastly, further literature suggests that these other forms of integration could be useful in managing the issue of balancing time-of-day use due to similar orientations existing in building-based PV systems within a city [374].

4.5.5. Temperature mismatch in PV modules

Electrical mismatch within PV modules is not only caused by heterogeneous irradiance conditions, but can be present due to temperature imbalance either within a submodule string or within a string of modules [386]. Much of the research related to this performance hindrance comes from GPV measurements [387]. However, it is known that UPV deployments such as BIPV experience much higher temperatures throughout the day, as well as higher temperature ranges [388,389]. The predominance of literature related to temperature in BIPV modules is however simply related to determining the best form of modelling or understanding how to install modules to mitigate heat build up. Future research should address this aspect of electrical mismatch.

4.6. Recent publications

Recent publications examine solar deployment in diverse urban contexts through varied methods, emphasising performance optimisation and broader sustainability impacts. Vigkos et al. [390] and Ali et al. [391] focus on region-specific factors such as aerosols, clouds, and temperature fluctuations, demonstrating the importance of localised assessments for optimal system performance. Suanpang and Jamjuntr [392] illustrate how machine learning techniques can improve solar forecasting accuracy, highlighting the value of data-driven approaches. Heat mitigation through advanced surfaces is explored by Ziaeemehr et al. and Martínez et al. [393], while Correia et al. [394] integrates bio-based solar concentrators with temperature sensing to enable smart city applications. Studies on vehicle-integrated photovoltaics [395] and electrochemical energy storage [396] show the potential for solar to enhance mobility and building autonomy.

Several works also address feasibility and regional adoption, with Nica et al. [397] quantifying the CO_2 reduction benefit of PV in Finland and Agoundedemba et al. [398] outlining PV's promise for bridging Africa's energy gap. LiDAR-enabled rooftop analyses provide further insight into UPV potential [399,400], while Albajari and Aslan [401] use experimental testing of hydraulic storage to optimise energy generation. Partial shading remains a key challenge, prompting studies like Wen and Wang [402] to refine rooftop PV layouts, and Marc et al. [403] to compare low voltage direct-current vs. low voltage alternating-current, revealing efficiency gains in direct-current grids. Collectively, these research efforts reinforce the need for integrated, context-specific approaches—combining geospatial data, computational modelling, and innovative hardware in order to achieve more resilient and sustainable UPV systems.

Methodologically speaking, LiDAR and GIS-based approaches form a strong thread, enabling rooftop solar potential analyses [399,400]. Dynamic simulations and 3D modelling tools such as PVsyst, SketchUp, and Weather Research and Forecasting are similarly employed to optimise layouts, assess heat impacts, or compare design scenarios [402,404]. Literature reviews and theoretical frameworks shed light on building envelopes, green infrastructure, and policy landscapes [396,398,405]. Finally, economic and feasibility studies — sometimes using machine learning or other modelling techniques — underscore the importance of cost-effectiveness and emissions reduction in both urban and regional contexts [397,403].

The results of classifying these recent publications using the LDA showed that the mean TAS scores shifted downwards indicating that the subject matter of the compiled corpus members has changed. However, from the manual review it seems that the content of the research has not shifted substantially, still employing similar methods and investigating similar questions as previous research. Relative to the research topics that were synthesised from the ten topics though several papers are notable to discuss. First, McCarty et al. [359] introduce a high-resolution simulation framework for PV systems under heterogeneous conditions and compare it to a variety of other frameworks found in the literature. Their findings indicate that different levels of resolution are suitable for different analytical lenses, the relationship being primarily dependent on the spatial scale of the modelling task. Their findings agree with other research in the field that suggest the need for IV-curve based modelling and simulation whenever partial shading is present [362]. Next the work from Khan and Santamouris [404] found that rooftop PV panels have mixed thermal effects, offering cooling benefits at night but contributing to urban heat during the day. Their work is based on simulation and adds evidence to the claims that UPV alters the heat dynamics present in urban spaces, which is also suggested by other recent literature [406]. However, more work is required in this track and ideally based in controlled, large scale experimentation to validate or refute simulation-based claims. Lastly, recent work on LCA for PV has led to the creation of a tool set for estimating the embodied impact of PV devices, using a bottom up approach [407]. The uncertainty present in the findings from using the tool set suggest that incorporating these factors into suitability assessment is crucial for a proper and holistic understanding of UPV performance.

5. Limitations

Given the goal of the research was not a long-lived topic model, but rather the discovery of latent topics in the current research landscape and the interpretation of them into researcher-driven groups or agendas the development of a perfect model was not sought from the beginning, trading convergence for practicality. This is why the thematic research agendas are created in the previous section. The selected method for this review comes with certain limitations: the inability for the model to classify certain publications into one topic, the lack of access to a publication's full text, the initial search terms heavily influence the review process, the broadness of the reviewed content. This section delves into each of these limitations and recommend future reviews done using LDA consider each to improve the overall quality of the review process.

5.1. Mixed topics

The LDA enabled us to categorise this research with clear quantitative bounds, but as seen in Section 3.11, this method does not always provide a clear topic for a document. Despite this limitation and the broadness of the review this research finds that the more organised understanding of the research landscape of UPV is useful in determining where linkages may exist with disciplines outside of one's typical space. The mixed topics that were encountered and the related documents within them that were reviewed, provided several previously undetected thematic areas were uncovered. Therefore, while a limitation of the LDA-based approach, it was beneficial to the overall aim of the review.

5.2. Mischaracterised corpus members

In some cases the LDA labelled corpus members for a topic that they are not necessarily associated with given the meaning of the research. The mischaracterisation of these works stems from using similar language to the topic in which they were placed. For instance, in Section 3.6 Ju et al. [179] report on the findings associated with fire safety testing of two modules. This does not necessarily fit with the topic in which the publication was classified from a semantic point of view. Rather it was just a grouping of similar keywords, such as "radiative flux" or "heat".

5.3. Full text access

Initially for Topic 10 there were 60 publications that were considered central to the topic. However, through the review process 16 of these were removed due to either inaccessibility, non-English language, or relevance. In the other topics this removal process occurred but not at this scale and is therefore notable to discuss the items within the corpus that were removed due to relevance. During the initial filtering process (prior to the topic analysis) publications were removed due to irrelevance. This was due to the search terms picking up papers with titles that contained the words or parts of the words but were from different fields (e.g. "BOPV" or bovine polyomavirus instead of BIPV). In the case of this topic the irrelevant publications were from similar fields and covered similar topics to those of interest now, but often tangentially. For example in Bhattacharya et al. [408] the research investigates the performance of a monitoring system for waste disposal in urban households that is powered by a PV module. The mention of the module is in the abstract and other key words such as city and solar energy, but the scope of their research does not align with the scope of the research being reviewed in this review.

5.4. Initial search terms

There are further limitations to the review in how the corpus was assembled that stem from the search terms considered. It was found while reviewing the corpus members that the search terms likely excluded papers or groups of papers that are relevant to UPV but are written using a separate set of keywords, such as "solar community" or "solar radiation". Therefore this research notes for future research pursuing this method that defining the search terms to be as comprehensive as possible is key given that the LDA will still be reducing the overall workload of categorising the research. An example of this can be found in the UHI publications of Section 3.7. These publications contain no mention of PV devices or electrical energy generated from incoming solar radiation. They do however discuss "solar radiation" in cities from the perspective of heat gain and loss. It is understood from work such as Sailor et al. [9] that this is a key point of discussion within UPV and therefore decided to keep these publications as a part of the corpus. Lastly, as can be seen in Section 3.11.3 highly focused PV device research exists within the corpus that does not mention building integration or use in cities. This was discovered later on in the process and was not filtered out as it does have some relationship to the larger topic. Additionally, an adherence to the method of LDA was maintained by reviewing these mixed-topic-type papers.

5.5. Probabilistic topic modelling

LDA, as a probabilistic model, produces variability across different runs due to its dependence on random initialisation and sampling methods. This means that even when applied to the same dataset, multiple runs of the model may result in slightly different constructions of the topics. In the context of this study, LDA was used as a preliminary tool to structure the literature before interpretation of the results. Therefore, the resulting model and topics are not intended to serve as a definitive, long-term classification system. Rather they operate as an initial point from which to review the domain. While certainly a limitation, the probabilistic nature of LDA allows for the flexibility in categorising text across multiple topics. This is ideal in situations where research may be multi-disciplinary and contain relevant knowledge for multiple research agendas. In comparison with other recent reviews of the field similar gaps such as the focus on high resolution modelling, technology development, and waste heat can be seen. These points, coupled to the exploratory nature of the analysis suggest that small variations in the topic constructions due to changes in the sampler (e.g., Gibbs sampling vs. variational inference) or random state would not substantially alter the high-level conclusions drawn from the literature.

5.6. Broad review

Lastly, the broadness of the review limits the specificity with which conclusions can be drawn about the state-of-the-art. Also, this research cannot be definitive that the characterisation of the landscape is absolute. The former is understandable as it is expected that in future reviews for UPV, one of the research agendas discussed previously could be considered for a state-of-the-art review. The latter is more difficult to reconcile. However, this research found that in this process this research reviewed papers from disciplines that would have normally been less of a focus during a typical review process, given that the authors of this review come from architectural design and engineering and not material science which a large portion of the corpus could fit into. Additionally, it was noted throughout the review that the papers presented by the LDA and filtering process were not necessarily the highest-cited or most commonly read research, which is where many review methodologies such as the snowball approach stem from. This has enabled the review to be a broader in which voices are considered and what contexts become relevant for shaping of the research landscape.

6. Conclusion

In this review a large corpus of work relevant to the study of urban photovoltaics was assembled. Using natural language processing technique, Latent Dirichlet Allocation, ten research topics were formed from the corpus members corresponding to different thematic research areas. For each topic a portion of the publications contained within were reviewed to broadly describe the landscape of research surrounding the concept of urban photovoltaics. This data-driven review was followed by a manual interpretation of the topics and their related literature to form six thematic research agendas, which were discussed for research gaps and their relevance to additional literature. Then the limitations of the NLP-driven review approach were recorded so future research may improve on the selected method.

The urban photovoltaic research field is broad, as well as young. Research throughout the field seeks to understand in what contexts PV can be used to meet building and urban energy demand, stabilise grid security, and mitigate or abate greenhouse gas emissions. The reviewed research is done at a variety of spatial scales as well as temporal. In the review it was found that these scales are still largely detached with some work at the technology development scale being motivated by the larger potential on building-based deployment. However, future research particularly at the urban scale should take note of the developments in the technology research domains to improve assessment accuracy and account for uncertainties. As the use of PV in urban spaces is almost certain to grow in the future, this research stresses the importance of more standardised approaches to assessing performance before and after deployment to mitigate increases in the performance gap. Additionally, as UPV is likely to never have the same maximum potential as GPV due to the limitations of the boundary conditions, it is essential that this tradeoff is well understood. In investigating this , this research recommends parametric LCA approaches be applied to feasibility studies. Designed correctly, deployed urban photovoltaic systems (on horizontal as well as vertical surfaces such as facades) are capable of reducing carbon emissions over their lifetime relative to the carbon emitted during their production.

A summary of the gaps uncovered include a need to focus on multi-scalar research, the development of simulation and analytical frameworks that can efficiently allow for the modelling of partial shading, the inclusion of lice-cycle assessment in research, the need to focus on contextual and local solutions as well as global standards, and to improve the field's understanding of how to manage excess heat in integrated photovoltaic systems as well as how that heat impacts urban heat island and thermal comfort. Focusing future research on the identified gaps will contribute to expanded electrification, UHI reduction, and climate change mitigation goals through more precise understanding of performance and the thermal implications before deployment. This enhanced understanding can be used by designers and engineers to improve on the use of location and context specific technologies as well as the development by industry of better performing technology for urban contexts.

Declaration of generative AI in scientific writing

OpenAI's ChaptGPT4 was utilised in the naming process of the topics. This is documented in the methodology section of the paper. Other than this we declare that we have not used generative AI elsewhere in the review process, writing process, or figure generation.

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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Data availability

Data will be made available on request.

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