A review study about energy renovation of building facades with BIPV in urban environment

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Abstract

To support urban energy transition, energy retrofit of building stock plays a key role since the majority of existing buildings have inadequate performances in comparison to current energy regulations. At the same time, the need to increase the building retrofit rate in a sustainable way can find advantageous applications through local renewable energy systems (RES) such as photovoltaics. However, the energy demand of existing buildings (and energy retrofit measures) and the potential RES production have been generally considered as separated disciplinary fields so far. Conversely, a synergic and integrated approach can be more efficient in terms of time and/or costs and can bring to novel urban energy strategies and policies enhancing the energy retrofit rate and the integration of photovoltaic in buildings (BIPV).

Therefore, thanks to systematic analysis of the literature of these two disciplinary fields in terms of approaches, methods, tools and analysed characteristics, this paper aims at identifying their synergies, which can allow to set the basis for an integrated assessment of the urban BIPV retrofit potential for facades. Indeed, differently from other RES, BIPV, as multifunctional element, can both improve the energy performance of building envelopes and produce electricity from solar radiation in urban contexts.

Keywords: *urban energy demand, building facade retrofit, solar potential, BIPV*

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1 Introduction

Among the multiple challenges that cities have to deal with, the sustainable and rational use of energy represents one of the urban priorities, since it is widely recognized that cities are the places where a wide amount of energy is consumed. In order to tackle this issue, both European and Swiss governments recognize the need for policies and strategies for urban energy transition to address energy savings of buildings and decentralized local renewable energy systems (RES).

Indeed, buildings are considered as a high-energy consuming sector, especially when considering the existing building stock. From recent investigations (EU, 2017a; EU, 2017b), about 35% of European buildings are older than 50 years and about 75% of buildings have been estimated to be energy inefficient, involving the need for their energy retrofit to save energy and to reduce CO_2 emissions. Also, the Swiss Energy Strategy envisions the reduction of the energy demand of buildings as a key element to save energy but the annual retrofit rate of buildings corresponds to an amount of 1% (Streicher et al., 2017). Hence, the energy retrofit of existing buildings is still an urgent issue.

With regard to local RES that can be used in urban contexts, photovoltaics (PV) seems to have a great potential to provide sustainable electrical energy in the urban environment (Kammer & Sunter, 2016). In detail, integrating PV systems in buildings through Building-Integrated Photovoltaics/BIPV (Biyik et al., 2017; Ritzen et al., 2017) can support the energy transition of the construction sector (Shukla et al., 2017a), allowing to: (i) take advantage of existing urban surfaces without requiring additional surfaces or infrastructure, (ii) produce energy where it is required, especially considering the increasing electricity demand of the building sector (Enerdata, 2015), but also for multiple uses (e.g. production of electrical energy and/or thermal energy for heating or cooling) (Scognamiglio & Rostvik, 2013; Allegrini et al., 2015), and (iii) fulfil the building envelope requirements as stated in the EN 50583 and in the IEC-TS 61836.

In accordance with the need to pursue building energy saving and produce energy from local RES in urban areas, one of the possible strategies to be adopted in cities and urban districts can be represented by the BIPV retrofit of building facades.

1.1 BIPV retrofit of facades at the building scale

Façade retrofit represents an effective strategy to reduce building energy demand, as demonstrated by Martinez & Choi (2018) and Wu et al. (2017). Depending on the existing building envelope properties, climate conditions and techno-economic constrains, as well as legislative regulations, different façade retrofit solutions can be designed to improve the energy behaviour of the envelope, the indoor thermal comfort of building users and enhance the architectural quality of the building skin (Ma et al., 2012). Among others, a design option for façade retrofit is represented by the use of multifunctional BIPV elements, thus allowing to reach the above-mentioned goals and, at the same time, produce electricity from solar energy.

From scientific literature and market surveys, it arises that several BIPV products for facades are emerging (Shukla et al., 2017b; SUPSI-SEAC, 2017). Realizing BIPV facades is still a challenging task in comparison to roofs due to the presence of mutual shadings of buildings, urban obstacles, openings and other architectural elements, which can significantly affect the BIPV potential (Vulkan et al., 2018). However, the contribution of BIPV facades in retrofit intervention is not entirely negligible. Indeed, renovating the façades of an existing building with multi-functional BIPV elements can have relevant advantages, such as the possibility to achieve plus energy building goals (Frontini et al., 2014; Sorgato et al., 2018), the possibility to spread the energy production throughout the day thanks to different facades orientations (Brito et al., 2013), and their contribution to enhance energy performances of the envelopes (Chiu et al., 2015). Consequently, the BIPV retrofit of facades at the building scale is already considered an "*attractive solution for effectively and sustainably retrofitting building envelope*" (Martín-Chivelet et al., 2018). This is also proven by the existing scientific literature investigating the techno-economic aspects related to BIPV retrofit (Evola & Margagni, 2016; Aguacil et al., 2017; Scognamiglio, 2017) and the aesthetical/customization aspects

(Attoye et al., 2017; Saretta et al., 2017), which are of particular interest for citizens especially within urban areas (Naspetti et al., 2016; Sánchez-Pantoja et al., 2018).

1.2 The potential of BIPV retrofit of façades at the urban scale

If at the building scale the evaluation of the BIPV retrofit potential is achievable thanks to the availability of data about building geometry, urban context, energy demand, building envelope properties and solar irradiation calculation, at the urban scale it is not trivial to determine the urban BIPV retrofit potential of building facades. Indeed, collecting data about the potential of individual buildings for such a purpose is not a suitable method because it is time consuming and costly. Therefore, in this study, determining the urban BIPV retrofit potential of facades means the identification of vertical building surfaces at the urban level where both energy-retrofit (to reduce energy demand) and BIPV (to produce required energy) are possible and needed, with an approach that moves from the single building evaluation. By this integrated evaluation at the urban level, there is the chance to quantify the urban retrofit potential of facades with multifunctional BIPV elements, thus providing decision-makers with reliable data for supporting urban energy policies aimed at the energy transition of the existing building stock.

However, in current urban energy planning studies and practices for existing urban areas, a common approach is to consider the energy demand of the building stock (and, hence, the urban energy retrofit potential) in a separate way from the urban BIPV potential of buildings, except few examples such as in Theodoridou et al. (2012) and Groppi et al. (2018). Furthermore, distinguishing such two disciplinary fields generally involves also the development of two different policies and financial instruments – one for building energy retrofits and one for BIPV installations.

In this paper, with the aim to set the basis for overcoming the inefficient separation among these disciplinary fields, their review in terms of approaches, methods, tools and analysed characteristics is carried out in order to try to answer the following question: “*are there synergies between the two disciplinary fields, which can allow to develop an integrated approach to evaluate the urban potential for BIPV retrofit of facades?*”.

This has been done thanks to the literature analysis of the two disciplinary fields: on one hand, urban energy demand and envelope retrofit potential of buildings (section 3.1), and, on the other hand, the urban BIPV potential of façade (section 3.2). The former can be defined as the expected energy demand of buildings and the related energy-saving from energy-efficient measures applied on facades at the urban level, while the latter as the available solar energy that hits the facades at the urban level. The methodology for the analysis of the literature is described in section 2.

2 Methodology

As this paper is aimed at investigating whether there are synergies for an interdisciplinary assessment of the existing building stock to support urban BIPV retrofit of building facades, a preliminary fundamental step is the analysis of the two main disciplinary fields involved in this topic: on one hand, the buildings energy demand and envelope retrofit potential at the urban scale, and, on the other hand, the BIPV potential of facades at the urban scale. Indeed, the former allows to understand the need for envelope energy retrofit or, at least, which buildings need energy retrofit at the urban scale, and the latter allows to know the potential of solar energy for BIPV installations. In detail, the methodology for the review consists of four main phases (Figure 1):

- Phase I: literature search of studies about the two disciplinary fields (section 2.1);
- Phase II: selection of the relevant literature according to the boundaries (section 2.2) and definition of the review criteria (section 2.3);
- Phase III: analysis of the selected literature in accordance to the review criteria, as described in section 3;
- Phase IV: identification of synergies useful to understand if an integrated approach, in terms of methods, tools and analysed characteristics, for urban BIPV retrofit of facades is feasible (section 4).

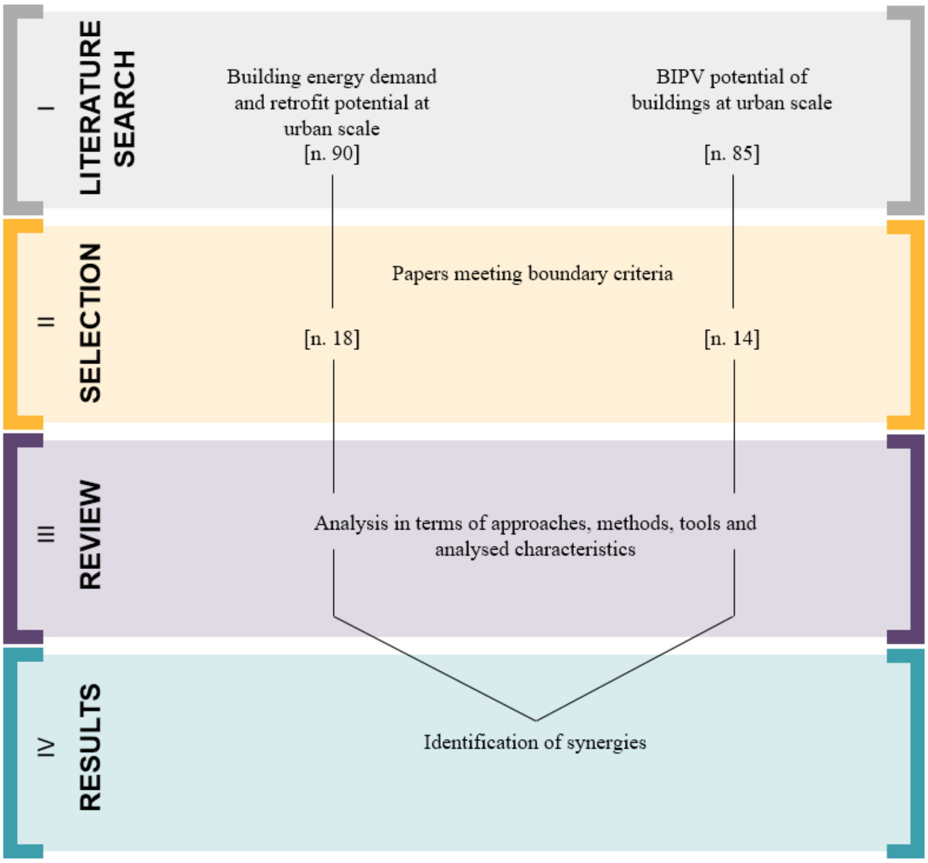

Figure 1 - Phases of the methodology for the review

2.1 Literature search

This phase has represented the preliminary step in the process of the literature review, allowing authors to collect several scientific works from the Scopus, Science Direct and Google Scholar databases about the two main disciplinary fields.

Specifically, for the studies related to the building energy demand and energy retrofit potential at the urban scale, the literature search has been focused on scientific works published since 2010, because in the last decade, the evaluation of the energy performance of buildings has shown a growth because of the development of advanced techniques and methodologies (Aghamolaei et al., 2018). The keywords that have been used to identify building energy demand and renovation potential at the urban scale have been “urban energy demand”, “building stock energy demand”, “urban energy modeling”, “urban energy saving”, “building renovation” and “building energy performance” as keywords. The total number of papers found was 90. In this disciplinary domains, several studies have been developed focusing on different aspects, such as, among others, multi-scale issues (e.g.

Reinhart & Cerezo Davila, 2016), multi-criteria issues (e.g. Wang & Holmberg, 2015), and/or data retrieving issues (e.g. Cajot et al., 2017; Caputo & Pasetti, 2015).

The literature search has been focused on scientific works published from 2010 also for studies related to the urban solar potential for existing urban areas. Indeed, from 2010, Sustainable Energy Action Plans (SEAPs) have been introduced in European countries as a voluntary procedure to develop and adopt actions and measures aimed at reducing CO_2 emissions and energy demand, also thanks to the analysis of the RES potential. Thus, from the need to quantify urban RES potentials, also solar energy potential studies have been developed. In this case, the keywords used in the above-mentioned databases are "urban solar potential", "solar energy estimation", "photovoltaic potential", "solar urban planning", "solar maps", "solar potential analysis" and "BIPV potential". The total number of papers found was 85. Several studies have been retrieved and it arises that they have been developed with attention to a plenty of aspects, such as, among others, the influence of the urban morphology (e.g. Sarralde et al., 2015; Chatzipoulka et al., 2016), the data source (e.g. Lukac et al., 2013; Martin et al., 2015), the solar irradiation calculation method (e.g. Martinez-Rubio et al., 2016).

2.2 Boundaries for the literature review

In order to provide a meaningful review of the two disciplinary domains in accordance with the objective of this study, some boundaries have been set by authors.

2.2.1 Studies about buildings energy demand and envelope retrofit potential at the urban scale

For this disciplinary field, only studies characterized by a bottom-up approach and capable to include building and envelope properties have been included in the analysis. Indeed, in accordance with the classification performed by Swan & Ugursal (2009) and Kavgic et al. (2010), energy demand of the building stock can be calculated by choosing two main approaches: the top-down approach, to obtain energy consumption maps or heat-maps using historical aggregated data about macroeconomic parameters at regional and national levels (e.g. energy price and income) and other parameters related to the city (e.g. population density and urban morphology), and the bottom-up approach that allows to combine disaggregated data of individual buildings to assess the energy consumptions ranging from the community level up to urban levels (Frayssinet et al., 2018). If the former considers the city or the nation as a whole, without accounting for the individual entities (e.g. buildings), the latter relies on building-related data, so that it is particularly advantageous when energy data about buildings are available. Even though this can involve more calculations because of the huge amount of information, the bottom-up approach permits to characterize the energy performances of the urban building stock taking into account more specific information about individual elements of the built environment and, for this reason, it is suitable for a more accurate quantification of the urban BIPV retrofit potential of facades. Another emerging approach is represented by the hybrid approach that has been developed in order to analyse the energy performance of neighbourhoods and urban districts by means of the combination of statistical and building physics methods, for instance using both available real data about buildings and statistical data when real information are not available. Figure 2 describes different models and methods used for bottom-up approaches.

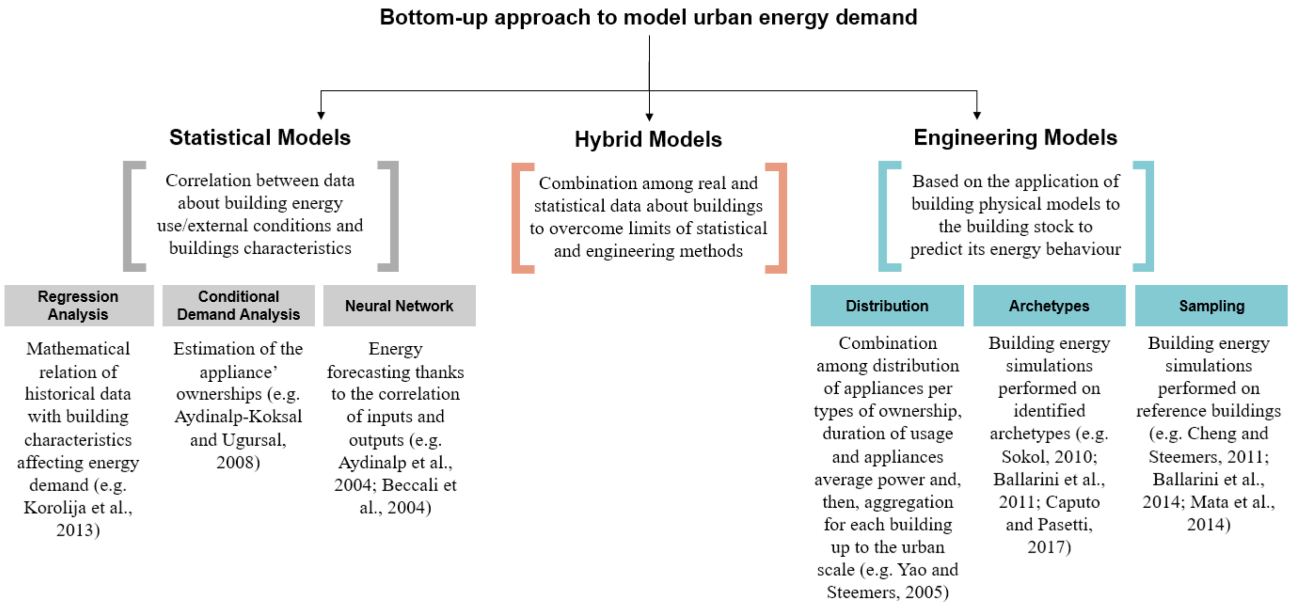

Figure 2 - Bottom-up approach: models and methods to determine building energy demand at the urban scale

2.2.2 *Studies about BIPV potential of facades at the urban scale*

The BIPV potential at the urban scale is generally calculated starting from the solar energy potential assessment with further technical hypothesis on BIPV. Indeed, as defined by Mainzer et al. (2014), PV potential can be classified into four categories:

- Theoretical potential: the total yearly solar irradiation received in a geographical area without considering any limitation, such as geographical or technical obstacles,
- Geographical potential: the total yearly solar irradiation integrated over building surfaces, suitable for the installation of solar energy systems,
- Technical potential: the generated energy from solar energy systems, calculated starting from the geographical potential and taking into account PV module and system efficiency,
- Economical potential: the technical potential that is economically exploitable, considering market prices for systems, energy tariffs and the expected system lifetime.

Considering that the focus of this study is on building facades, only potential studies capable to consider building vertical surfaces are selected, thus involving that the choice of geographical, technical and economical BIPV potential studies about existing facades where approaches, methods, tools and analysed characteristics are reported. For instance, studies about the relations between the urban morphology and the solar potential are not considered in this analysis since they provide information for a preliminary investigation, generally without providing quantitative data about the BIPV potential on building surfaces.

2.3 Criteria

The review criteria for the analysis of the literature have been defined by authors with the aim to identify synergies among the two disciplinary fields in terms of approaches, methods, tools and analysed characteristics. In detail, the criteria are the followings:

- scale: the size of the urban area and the number of analysed buildings (if available),

- spatial model: the type of model to describe the urban environment used as input for the calculations,
- aim: the specific aim set by authors,
- method: the method used and/or developed by authors to achieve the proposed aim,
- tools: instruments used for the calculations.

In addition to these, authors included also criteria related to the most investigated characteristics, which have been subdivided into three main levels:

- envelope characteristics, such as transmittance, state of conservation, constructive properties, etc…,
- building characteristics, such as building types, construction year, geometrical features, etc…,
- urban characteristics, such as effects of nearby buildings, vegetation, etc….

In particular, the specific investigated characteristics are not defined *at priori* but they are listed one by one depending on their appearance in the analysed studies. In such a way, every specific characteristic can be included, thus proving a complete overview of the state of the art.

3 Results of the review

As a result of the application of the boundary criteria, the selected studies of the two disciplinary fields are in the amount of 18 for the buildings energy demand and envelope retrofit potential, and in the amount of 14 for the urban BIPV potential of facades. These studies are reported and analysed in Tables 1 and 2.

3.1 Buildings energy demand and envelope retrofit potential at the urban scale

From the analysis of the selected studies, it arises that the energy demand and the retrofit potential of buildings at the urban scale are evaluated for both urban districts and large cities. The majority of these evaluations ground on 2D georeferenced maps of the building stock, which are generally imported into GIS software. Indeed, thanks to GIS, other information can be added, for instance to obtain 2.5D urban models, or can be managed to carry out analysis of the energy demand. It is interesting to note that, so far, only the study of Chen et al. (2017) relies on the 3D city model that is combined with GIS to include building-related data, which can be visualized by users on a web-tool.

Although all the studies assess the energy demand of the building stock by adopting a bottom-up approach, different methods and models are developed and/or implemented by authors: some of them are characterized by statistical models (e.g. Howard et al., 2012; Mastrucci et al., 2013; Evola et al., 2014; Mutani et al., 2016; Belussi et al., 2017; Moghadam et al., 2018) and others by engineering models (e.g. Ren et al., 2012; Ascione et al., 2013; Caputo et al., 2013; Braulio-Gonzalo et al., 2016; Österbring et al., 2016; Kazas et al., 2017; Serrano-Jimenez et al., 2017) or hybrid methods (e.g. Fonseca & Schlueter, 2015). Furthermore, some of the analysed studies address also strategies for the building retrofit providing some reference scenarios (e.g. Mastrucci et al., 2013; Delmastro et al., 2016; Evola et al., 2016), even though very few consider RES. For instance, Serrano-Jimenez et al. (2017) and Gupta et al. (2018) take into account the option to include RES in the retrofit process but without assessing their urban potential. In addition to the above-mentioned aspects, this analysis shows that the most common tools used in engineering and hybrid methods are building energy simulation tools, such as EnergyPlus and TRNSYS. With regard to the analysed characteristics, it is necessary to highlight that their appearance in the analysed studies depend on the available datasets and on the method chosen by authors. For instance, engineering and hybrid methods are generally capable to include both building characteristics, such as geometrical features, intended use and construction period, and detailed data also about the building envelope characteristics such as thermo-physical properties (e.g. Caputo et al., 2013; Fonseca & Schlueter, 2015), whereas statistical methods rely on less detailed data, also at the building cluster scale (e.g. Howard, 2012).

Even though this literature review can be not fully exhaustive, it arises that few studies include the evaluation of the building orientation and the influence of the urban context, as well as the state of conservation and the last building retrofit. Although the state of conservation and the last building retrofit can be omitted in a preliminary study about the energy consumptions of the building stock, they represent fundamental information for the next assessment of envelope energy retrofit potential

(Dall’O’ et al., 2012), that generally represents the following step of urban energy policies aimed at a more sustainable built environment.

Year	Author	Scale	Aim	Spatial Model	Method	Envelope characteristics	Building characteristics	Urban characteristics	Tools
2012	Dall’O’ et al.	Urban (8005 buildings)	Estimation of the urban retrofit potential for residential buildings	2D map of the building stock	Each building is described	Geometrical features: opaque and transparent surface Material type State of conservation Historical constrains	Geometrical features: volume and floor area Orientation Construction Period Heating demand		GIS software to store, analyse and visualize data
2012	Howard et al.	Urban (1 million buildings)	Estimation of buildings energy end-use intensity for space heating, DHW and *electricity*	2D geo-rectified database	Multiple linear regression statistical analysis using data depending on ZIP codes instead of buildings’ construction type or age		Total building floor area per zip code (divided in 8 building’s typology)		
2012	Ren et al.	Urban / Regional (n.a.)	Assessment of total building energy consumption with hourly resolution considering building construction and materials, appliances, local climate and occupancy patterns	2D housing stock model developed using census data	Building physics model to obtain end-use energy evaluation by the aggregation of hourly consumptions for representative buildings (288)	Envelope transmittance values for opaque and transparent elements	Geometrical properties Building type Construction period User profile		AusZEH tool
2013	Ascione et al.	District (573 buildings)	Characterization of the energy performance of new and existing buildings	2.5D municipal model	Energy consumptions are calculated for each building	U-values (opaque and transparent elements) defined depending on building’ types Contiguities of envelopes	Geometrical properties: floor area, perimeter, volume Building type Construction period Orientation Ventilation rate and indoor heat gains defined depending on building’ types	Adjacent buildings and specific orientations	GIS software to store, analyse, visualize data EnergyPlus

2013	Caputo et al.	Urban (≈ 64.000 buildings)	Assessment of buildings' energy consumptions for a city or a district and evaluation of the effects of different energy strategies	2.5D municipal model	Statistical model using building' archetypes	Thermo-physical and constructive characteristics for the defined archetypes	Geometrical properties: floor area, perimeter, volume Building type Construction period Orientation		GIS software to store, analyse, visualize data EnergyPlus
2014	Mastrucci et al.	Urban (300.000 dwellings)	Identification of energy consumption profile and savings potential of large residential stocks	2D map of the building stock	GIS-based bottom-up statistical models using a multiple linear regression method		Number of occupants and floor area per dwelling. Electrical energy and natural gas consumptions per dwelling.		GIS software to store and analyse information
2015	Fonseca and Schlueter	Urban (1392 buildings)	Assessment of spatial and temporal variations of the energy demand of buildings	2.5D map geo-referenced database and digital elevation model of the area	Hybrid approach: data from local building archetypes are used in a novel dynamic building energy model	Geometrical features: window to wall ratios Thermo-physical properties (opaque and transparent elements)	Geometrical features: area, height Orientation and urban context Construction year and last renovation Occupancy types Generation system	Surrounding environment	GIS software to store, analyse, visualize and disseminate data Model for energy calculation EnergyPlus for validation
2016	Braulio-Gonzalo et al.	District / Urban (n.a.)	Assessment of the energy demand for heating and cooling and indoor thermal comfort of residential buildings	2.5D map geo-referenced database	GIS-based prediction method capable to combine building physics modelling and statistical inference	U-value for opaque and transparent elements	Orientation and urban context Building type Year of construction Shape factor (S/V)	Urban block type Street height-width ratio Specific orientation	GIS software Dynamic building simulation software
2016	Delmastro et al.	Urban (5585 buildings)	Development of a bottom-up approach for investigating the socio-economic feasibility and technical suitability, from a	2D map of the building stock	Thanks to the characterization of the building stock, reference buildings (RF) are identified. Association of energy performances	Construction materials Share of transparent envelope surface	Destination use Construction period Shape factor (S/V) Percentage of heated volume	Contiguous buildings for RBs	GIS software

			policy perspective, of different renovation measures at the urban level		to RBs. Definition of urban cost-optimal level of energy performance, socio-economic feasibility factors and scenarios				
2016	Evola et al.	District (458 buildings)	Definition of the space heating demand for residential buildings	2D map of the building stock	Statistical model based on regression methods has been used to define the primary energy consumption	U-value of each building element	Geometrical characteristics: buildings size and shape Age of construction		GIS for representation
2016	Mutani et al.	Urban (n.a.)	Assessment of urban residential space heating consumptions	2D map of the building stock	Buildings are classified according to their volume, construction period and to the surface to volume ratio. Association of a space heating energy consumption value to the buildings with two different methods: reference buildings (RB) and linear regression (LR)	Geometrical characteristics (external surface) Material/structural properties	Geometrical data from GIS database and Census database (S/V, construction period)		GIS open source tools and TRNSYS (for RB)
2016	Österbring et al.	District (433 buildings)	Development of a methodology for building-stock description using building-specific data and measured energy use	2.5D GIS model	Engineering model	Envelope area U-value based on an age-type classification	Geometrical data Energy data: type of heating, HVAC systems, no. of stories, no. of staircases, attachment to other buildings and heated floor area Construction year		GIS software and EABS model (Energy Assessment of Building Stocks)
2017	Belussi et al.	District / Urban (n.a.)	Estimation of the energy consumptions and performances of buildings	2D map of the building stock	Statistical model to classify buildings into categories based on standard open-source data		Dimensions (height, surface and volume) Intended use Period of construction		GIS software

2017	Chen et al.	District (940 buildings)	Analysis of the potential retrofit energy and cost savings of city districts through the open web-based platform CityBES (City Building Energy Saver)	3D city model	Definition of UBEM based on CityBES platform that allows to select and analyse energy retrofit measures for each building of the district	Envelope insulation	Building footprint Building type, Building height Construction year Number of stories Lighting systems HVAC systems Equipment efficiency	Shading Neighbourhood buildings Shared walls	EnergyPlus and OpenStudio Simulation Engine GIS software
2017	Kazas et al.	District (twelve buildings)	Definition of detailed overall thermal energy demand profile		Engineering model based on samples of the representative building	Air infiltration	Geometrical properties Shadings Internal loads		EnergyPlus
2017	Serrano-Jimenez et al.	District (n.a.)	Estimation of the residential district retrofit potential		Reference building	Permeability and thermal transmittance of walls and windows Permeability of windows Solar factor	Heating, cooling and domestic hot water demands		Building energy simulation tool
2018	Gupta et al.	Districts (n.a.)	GIS-based approach that combines available national and local data on buildings and energy to provide targeted low carbon measures	2D map of the building stock	Identification of urban areas suitable for retrofit and individual building evaluation for retrofit	Wall construction U-values Transparent area	Construction year Geometrical data (S/V) Roof area and orientation Existing solar energy systems Estimated energy consumption data		GIS-based energy model with calculation from other software (DECoRuM, BREDEM-12 and SAP 2009)
2018	Moghadam et al.	Urban (3600 buildings)	Estimation of the energy consumptions of residential buildings for heating space	2.5D map of the building stock	2D/3D GIS-based approach combined with a multiple linear regression	U-values for opaque surfaces and transparent surfaces	Geometric data (S/V, floor area, no. of floors) Construction period Building type Monthly space heating consumptions		GIS software

Table 1 - "Bottom-up" studies developed for assessing energy consumptions or for estimating energy retrofit potential in urban areas

3.2 BIPV potential of facades at the urban scale

Of the 85 studies collected from the literature search, only 14 are related to the geographical, technical and economical BIPV potential of facades at the urban scale. Even though some of them assess also the roofs potential, the analysis is focused only on aspects related to the estimation of the BIPV facades potential. All of 14 studies propose methods for predicting the BIPV potential of the existing facades on the district and city scales. Nevertheless, the majority evaluate the BIPV potential in terms of received radiation (geographical potential) and generated energy (technical potential) and only the studies of Fath et al. (2015) and Brito et al. (2017) assess also the economic benefits (techno-economic potential).

Even though this review can be not fully exaustive, the approches developed or adopted in the selected studies for the calculation of the BIPV potential on facades are bottom-up and they can be categorized into three main categories, as shown also in Figure 3:

1) Approaches based on real/statistical building surface data

   The methods that are used for this kind of approach are generally based on real/statistical building surface data and correction factors according to façade/envelope types such as in the study developed by Dias et al. (2015);

2) Approaches based on 3D models with solar irradiation simulations

   Urban environment can be modelled with 3D features (e.g. starting from CAD or CityGML data) and, thanks to specific software (e.g. Radiance) the solar irradiation can be computed considering building obstructions by means of detailed models or using correction factors, which reduce the total roof/façade area to obtain the suitable area for solar systems. Examples of this approach are the works of Caamaño-Martin et al. (2012), Lobaccaro et al. (2012), Amado and Poggi (2014) and Fath et al. (2015);

3) Approaches based on GIS methods

This is the widely used approach. Indeed, GIS methods generally allow to use 2.5D or 3D models of urban areas as inputs and to represent the output of the radiation algorithm applied to building surfaces. An exhaustive review of the radiation models and tools can be found in Freitas et al. (2015). However, from the selected studies, the most common tools for solar radiation calculations are “SolarAnalyst” (Fu and Rich, 1999), “r.sun” (Súri and Hofierka, 2004), “SOL” algorithm (Redweik et al., 2013) or specific algorithms developed by authors, such as Catita et al. (2014), Karteris et al. (2014), Liang et al. (2015), Bremer et al. (2016) and Wegertseder et al. (2016).

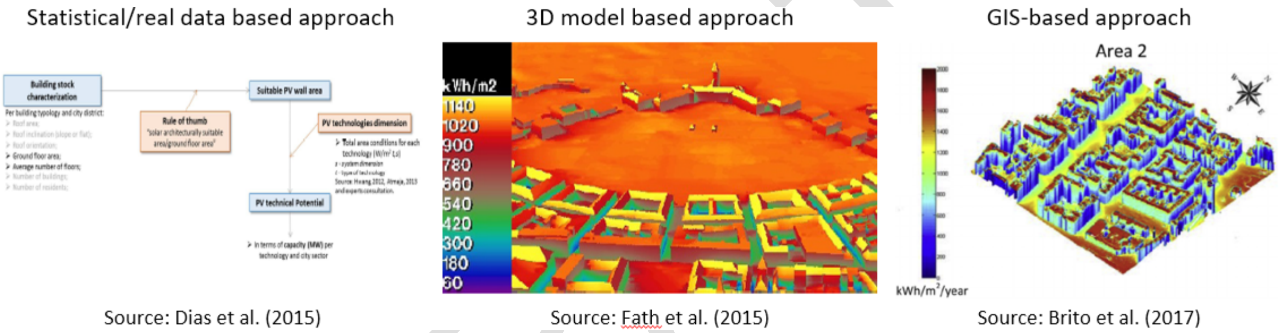

Figure 3 - Examples of the three categories of approaches to assess the urban BIPV potential of facades. It is worth to note that the 3D model based approach image is similar to the GIS-based approach image. However, the process to acquire the city model is different.

Independently from the adopted approach, since solar irradiation is time and weather dependent, an important aspect is related to the temporal fluctuation of energy production that has been taken into account by Redweik et al. (2103), Catita et al. (2014) and Brito et al. (2018). Even though knowledge about hourly production data can be strictly dependent on the calculation method, it can be very useful to assess the energy self-sufficiency of buildings. This is suitable especially for small districts, since for larger urban areas it is difficult to manage hourly data about energy generation and demand.

Furthermore, what is interesting to note is that the majority of the studies relies on 2.5D or 3D urban models, which are necessary to evaluate geometrical dimension and orientation of facades to calculate the BIPV potential.

However, the architectural characteristics of facades (e.g. openings, balconies, cornices…) are generally not included in such urban models but their influence on the real BIPV potential is considered thanks to a second phase where reduction factors are applied, such as in such as in Amado & Poggi (2014), Dias et al. (2015), Fath et al. (2015), Wegertseder et al. (2016), Brito et al. (2017) and Vulkan et al. (2018). With regard to the urban characteristics that are included in the BIPV potential calculation, this review shows that the shadow of nearby buildings is considered in the majority of the cases, while few studies are capable to consider the influence of the vegetation (e.g. Redweik et al., 2013; Bremer et al., 2016; Brito et al., 2017) and only one considers mutual reflections (Fath et al., 2015).

Finally, it is important to note is that BIPV facades play fundamental roles, indeed, as demonstrated by Fath et al. (2105) for a high-density urban area where the solar potential of roofs is in the amount of 53% while the solar potential of facades represents the remaining 47% and by Vulkan et al. (2018) for high-rise buildings. Even though such a distribution can vary depending on the urban morphology, the contribution of facades for energy production is relevant to be taken into account.

Year	Authors	Scale	Aim	Spatial model	Method	Envelope characteristics	Buildings characteristics	Urban characteristics	Tools
2012	Caamaño-Martin et al.	Urban (two districts of 376 + 710 hectares)	Geographical potential of facades and roofs	3D model from survey	Detailed GIS database of each facade and roof with info about active solar potential, that is computed by means of the software tool of the Solar Energy Institute (Instituto de Energía Solar – TU Madrid)	Structural characteristics from 3 roof and 3 façade typologies		Shadows due to nearby buildings	Tool of the Solar Energy Institute
2012	Lobaccaro et al.	Urban (n.a.)	Geographical potential of facades	3D model	Development of a tool (SolarPW) to evaluate the mutual overshading between two buildings			Shadow of one nearby building	SolarPW
2013	Redweik et al.	Urban (area of about 160'000 m^2)	Technical potential of facades and roofs	3D model from elaboration of airborne LiDAR data	From LiDAR data a 3D model is generated. Then, the method (algorithm SOL) combines it with a radiation model and the astronomical model to calculate the solar radiation with a high spatial resolution. Moreover, "the method calculates hourly shadow maps and facade shadow maps for the estimation of the direct radiation as well as a sky view factor map and facade sky view factor for the estimation of the diffuse radiation"	No windows, no balconies	Geometrical features Orientation	Trees and building shadows. No reflections	MATLAB
2014	Amado & Poggi	Urban (n.a.)	Technical potential of facades and roofs	3D urban model	An urban area is subjected to a solar analysis by means of Ecotect and data are extrapolated to GIS	Roof typologies, shading elements (utilization factors)	Geometrical features Orientation	Shadow effects of nearby buildings	Autodesk Ecotect
2014	Catita et al.	Urban (n.a.)	Geographical potential of facades	3D model from DSM and airborne LiDAR data	MATLAB® algorithm, called SOL, that takes DSM, astronomical model and radiation model to obtain global radiation on vertical facades, implemented in GIS environment		Geometrical features Orientation	Shadow effects of nearby buildings	MATLAB

2014	Karteris et al.	Urban (n.a.)	Technical potential of facades	Creation of a 2.5D model from DSM and DTM	Evaluation of the most suitable building's typologies for PV. The selected archetypes have been subjected to dynamic energy simulation to calculate the solar potential, the energy output, the energy payback period and the CO_2 savings. Then, through GIS, the effect of shadows is considered with empirical rule	Morphology of the facade, WWR, row balconies, U values of facades	Geometrical features Orientation	shadow effects of nearby buildings	
2015	Dias et al.	Urban (n.a.)	Technical potential of facades and roofs	No 3D models are used	Methodology to assess the domestic solar water heating, thanks to the collection about roofs number, area, inclination, orientation as well as restriction, the suitable area for solar thermal systems has been calculated through correlation factors with the ground area of buildings, by building typology and city district. Same methodology for BIPV	Shading due to roofs elements are considered by means of reduction factors			
2015	Liang et al.	Urban (n.a.)	Geographical potential of facades and roofs	3D model required	Development of a computation engine - SURFSUN3D - that, thanks to the 3D model and the r.sun model, calculate solar irradiation		Geometrical features Orientation	Shadow effects of nearby buildings	GRASS GIS r.sun
2015	Wieland et al.	Urban (13'000 buildings)	Geographical potential of facades and roofs	CityGML 3D city model of Karlsruhe	Solar radiation is calculated on a 3D urban model on each surface thanks to point grids on building surfaces. Then, the solar irradiation income for each point (reflection not yet) is computed considering the shadows at a particular time step		Geometrical features Orientation	Shadow effects of nearby buildings	Python script
2016	Bremer et al.	Urban (n.a.)	Geographical potential of facades and roofs	3D model from geometries, 2.5D DEM and 3D-voxel	Creation of the 3D model from different data set and implementation of a radiation model (based on standard ray-tracing) with a texture approach to calculate the solar potential	Roof overhangs		Shadow effects of nearby buildings and vegetation	GIS SAGA improved module
2016	Fath et al.	Urban (n.a.)	Techno-economical potential of facades and roofs	3D city model	Assessment of the potential in LOD2 by means of Radiance simulations	Utilization factors for roofs/facades and for historical, structural or architectural reasons	Geometrical features Orientation	Shadow effects and mutual reflections of nearby buildings	Radiance

2016	Wegertseder et al.	Urban (n.a.)	Technical potential of facades and roofs		1st sub-model: solar potential map from the solar radiation + topography (Cercasol). Definition of 6 urban zones analysed with URBES model for obstructions. ArcMap to assess potential. 2nd sub-model: energy system model	Reduction factors are used to consider architectural elements	Geometrical features Orientation	Obstructions due to nearby buildings and topography	
2017	Brito et al.	Districts (244 + 294 buildings)	Techno-economical potential of facades and roofs	DSM from LiDAR	Development of 3D PV potential tool based on LiDAR data and reference meteorological data to estimate solar irradiation of all points of the study area (ground, roof and facades). The obtained results about PV generation are compared with electricity demand	Fixed reduction factors for openings	Geometrical features Orientation	Nearby buildings Vegetation	GIS SOL algorithm
2018	Vulkan et al.	District (360)	Technical potential of facades and roofs	2.5D model	Development of R package for spatial and temporal calculation of shadows. From the solar irradiation, the building capacity for BIPV is provided. Finally, a comparison between electricity generation and demand is provided.	Fixed reduction factors for openings	Geometrical features Orientation	Shadows of nearby buildings	GIS R language

Table 2 – Studies about estimation of urban solar potential of facades

4 Discussion

This study has investigated the disciplinary fields of urban energy demand and envelope renovation potential of buildings, and the disciplinary field of urban solar energy potential by analysing their approaches, methods, tools and analysed characteristics.

Specifically, from the literature review, it arises that, from the point of view of the adopted approaches, to obtain detailed data of the building stock, both the disciplinary fields are characterized by a bottom-up approach. Indeed, even though bottom-up approaches can rely on assumptions about buildings characteristics and properties, they are capable to provide the building energy demand and/or the retrofit potential, as well as the solar potential of building envelopes at the urban scale.

Conversely, from the point of view of the adopted methods, the authors found differences in terms of aims and implementation methods. Indeed, for buildings energy demand and envelope retrofit potential studies, statistical methods or engineering methods are usually implemented, differently from BIPV potential studies, which generally implement only engineering methods.

Depending on the method, different tools can be used to calculate the building energy demand and the energy retrofit potential, as well as the solar potential at the urban scale. Besides this, it emerges that GIS-based tools are often used in both disciplinary fields because they are suitable to store, analyse, visualise and manage data at the urban level. For instance, GIS is often used also to assess the solar irradiation over building surfaces by means of specific extensions, as well as to collect and manage energy-related data about buildings at the urban scale.

With regard to the analysed characteristics, both fields require geometrical information about buildings but, if building energy demand estimation at the urban scale can ask for surface and/or volume data independently from orientations, solar energy potential studies necessitate more detailed geometrical data, with 2.5D or 3D models to compute solar radiation on facades. In addition to this, it is necessary to note that for the calculation of the building energy demand and the energy retrofit potential, further data are required such as information about the envelope (e.g. window to wall ratio, thermal transmittance values), construction periods and last renovation, among others, whereas solar energy potential studies generally use utilization factors to include envelope characteristics (such as window to wall ratio).

Even though there are some differences in terms of implementation methods and tools among the two disciplinary fields, some synergies can be identified, as shown in Figure 4.

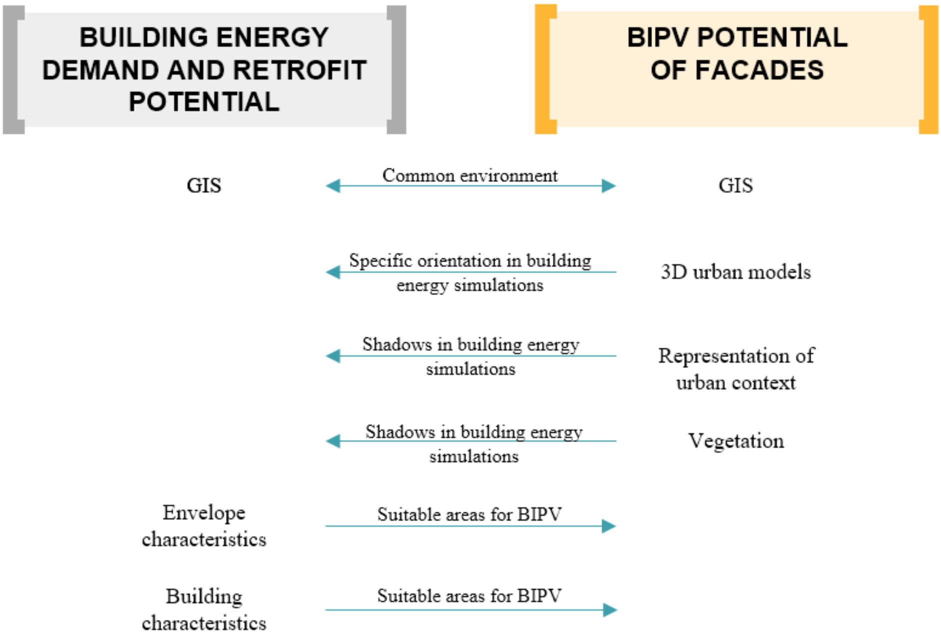

Figure 4 - Synergies among the two disciplinary fields

Firstly, both the disciplinary fields ground on GIS that can represent the common environment for an integrated assessment of urban BIPV retrofit potential of building facades. Secondly, the recent development of 3D city models has led to novel calculation methodologies and techniques of the solar energy potential of building façade in urban areas (e.g. Bill et al., 2016; Cheng et al., 2018), but such urban 3D models can be also a useful database for improving the building energy demand and retrofit potential estimation at the urban scale (Biljecki et al., 2015), since they allow to increase the accuracy of building geometrical data, as well as for providing information about building orientations and mutual shading between buildings. Moreover, considering that 3D urban models can also include vegetation, this can allow to consider the effect of urban micro-climate on the evaluation of the urban energy demand of buildings.

Thirdly, data about building and envelope characteristics, such as window-to-wall ratio, thermo-physical properties, construction or renovation years, state of conservation, which are generally collected for the assessment of the building energy demand and the retrofit potential, can be used to detail the assessment of the BIPV potential of facades and to determine the suitable building surfaces for BIPV installation in accordance to a technological perspective.

By considering these possible synergies, the current approach characterized by the separation among the two disciplinary fields can be overcome in favour of a more integrated approach capable to determine the potential of retrofitting existing building surfaces with BIPV at the urban scale. In detail, among possible drivers for achieving this goal, one of the most promising is represented by the recent spread of 3D city models together with the combination of the available building data related to the two disciplinary fields. Indeed, even though obtaining this amount of data and urban 3D models can be not trivial, their combination and the development of a comprehensive information GIS database about the building stock (including energy demand, need for energy retrofit, BIPV potential) can allow to obtain a clear integrated assessment of the urban potential for BIPV retrofit of facades. In the framework of the integration of energy retrofit and BIPV potential, hourly based evaluations assume particular importance, as cited from some authors (e.g. Redweik et al., 2013; Catita et al., 2014 for solar potential studies, and Fonseca & Schlueter, 2015; Kazas et al., 2017 for energy needs studies). Nevertheless, for the investigation of the BIPV retrofit potential of facades at the urban scale, the seasonal time-frame can be considered as a preliminary evaluation for further investigation at smaller scales (e.g. district or cluster of buildings), including hourly based dynamic simulations, aimed at balancing energy retrofit solutions and PV production with appropriate time resolution.

5 Conclusions

Thanks to an extensive literature review, this paper provides an innovative contribution related to the identification of common approaches, methods, tools and analysed characteristics to investigate whether the disciplinary field of urban energy demand and envelope renovation potential of buildings, and the disciplinary field of urban solar energy potential present synergies.

Indeed, in current urban energy planning, building energy demand together with retrofit potential studies and RES potential studies have been considered as separated disciplinary fields so far. In particular, the authors have found that there is no evidence of studies capable to integrate such disciplinary fields for the evaluation of the BIPV retrofit potential of facades with the same accuracy since the preliminary phases of the urban energy retrofit process, causing to lose the opportunity to develop synergic and integrated policies and actions, needed for urban energy transition.

However, thanks to an extensive systemic analysis of the literature carried out by authors, it arises that there are some main synergies. Indeed, even though this study is a conceptual investigation, the emerging results about synergies suggest that an integrated evaluation of the BIPV retrofit potential can be developed starting from the combination of the available datasets of the two disciplinary fields since the early stage of the energy retrofit process. This innovative approach could support stakeholders (researches, urban planners, public administrators etc.) in combining available databases, belonging to the two disciplinary fields, in order to provide the necessary information for the development of operational methodologies and tools capable to assess the potential of building facades to be renovated with BIPV. For example, a comprehensive GIS-based database, able to include the geometrical and energy-related characteristics of the building stock, can be envisioned as an effective support for definition of the policies and of the measures toward the renovation of the building stock by multifunctional BIPV elements.

In conclusion, this review provides the theoretical basis for supporting the development of operative methodologies aimed at promoting the implementation of BIPV facades in wide energy retrofit processes at the urban level. In particular, further developments will mainly focus on the definition of a GIS-based interface in order to combine energy-performances and BIPV potential data and on the application of this tool to an existing case of study.

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