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Initial approximation of the implications for architecture due to climate change

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ABSTRACT

This review paper organizes and summarizes the literature regarding climate change impacts on future building energy demand. The approaches used for the creation of future weather climate and building renovation scenarios, as well as building energy modeling at different scales, are evaluated. In general, it can be concluded that future heating demand could decrease (7–52%), while cooling demand could increase significantly (up to 1050%). The decrease/increase rates varied significantly depending on the climate and case study building(s) considered, with buildings and building energy systems located in extreme climates being more sensitive to such changes. The main uncertainty of the predicted increase/decrease rates can be assigned to climate models and forecasted weather data. Nonetheless, such forecast and risk assessment are necessary for sustainable development of urban environment and associated energy systems. Further development of dynamic large-scale building energy simulation tools is required, along with the development of large-scale building renovation measures and strategies that take into account additional aspects (such as economic and societal). Moreover, continuous efforts are required in further climate models' improvement and uncertainty reduction.

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KEYWORDS
Climate change; building modelling; architectural simulation; heating demand; cooling demand

Introduction and background

According to the World Resources Institute (World Resource Institute, 2014), 64.5% of global anthropogenic greenhouse gas emissions are caused by the energy sector. Worldwide, about 18% of total energy end-use is consumed in the residential building sector (U.S. Energy Information and Administration, 2013). However, in developed countries, residential sector is the major source of CO_2 emissions (Butera, 2010; Gupta & Gregg, 2012). In the U.S., for example, 44.5% of total CO_2 emissions comes from the building sector; a significantly higher share of emissions compared to the industrial (21.1%) and transportation

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(30.7%) sectors (Achitecture, 2030, 2013). Due to the predicted expansion of the global urban environment and an increasing global population (predicted to reach 10 billion in 2056 (United Nations, 2015)), migration from rural to urban areas (the current urban population of 3.9 billion is estimated to grow to 6.4 billion by 2050 (International Organization for Migration, 2015)), and increasing global gross domestic product per capita, the future reduction of energy consumption and related greenhouse gas emissions from the building sector presents a challenging task (it should be noted that the term 'building sector' used within this review corresponds to a combination of residential, commercial and industrial buildings).

Theoretically, buildings consume different forms of energy in order to provide comfort conditions for the inhabitants, and maintain their performance constant in time with respect to various variable conditions, such as climate (Pulselli, Simoncini, Pulselli, & Bastianoni, 2007). Buildings interact with and respond to their environment in complex ways, with temporally variable interactions between local weather conditions, internal heat loads (heat release from occupants, lighting equipment, and electronic appliances) and HVAC (heating, ventilating, and cooling) systems (Crawley, 2008). The majority of energy consumed in buildings is used for maintaining heating and cooling services. For example, this accounts for approximately 50% of the final energy consumption in the U.S. and E.U. (European Comission, 2016; U.S. Energy Information and Administration, 2013), where the ratio between heating and cooling load mainly depends on local climate characteristics.

Over the course of the last three decades, significant research efforts were made in order to reduce building energy consumption and provide sustainable heating and cooling solutions for the ever-growing urban environment. These research efforts mostly focused on building adaptation measures and the development of sustainable urban energy systems. However, the potential changes in future building energy demand were initially overlooked. Predicted increase in air temperature (according to all existing climate scenarios) will decrease the difference between the outdoor air temperature and building internal comfort temperature in heating-dominated climates, consequently reducing building energy demand (Makantasi & Mavrogianni, 2016). On the other hand, any increase in outdoor air temperature would increase the temperature difference between the outdoor and comfort temperature in cooling-dominated countries, resulting in increased cooling and thus overall energy demand (Makantasi & Mavrogianni, 2016). The impact of changing weather variables is addressed as the direct impact of climate change on building energy demand this review.

Due to climate change mitigation measures and policies, new directives have been legislated in order to improve building energy performance. For example, the European Parliament has legislated the Energy Performance of Buildings Directive (EPBD), or the Directive 2010/31/EU, which states that '*major renovations of existing buildings, regardless of their size, provide an opportunity to take cost-effective measures to enhance energy performance*' (European Parliament, 2010). Accordingly, renovation of the existing building stock could further decrease heat demand: with higher insulation levels, building heat losses to the environment decrease, consequently lowering heating energy requirements in cooler climates. On the other hand, the impact on cooling energy demand is not so obvious: in warmer climates, higher insulation levels could decrease heat gains from the environment during daytime (when the outdoor temperature is usually higher than the room comfort temperature) but also block heat release from the building to the environment during night-time (when the outdoor temperature is usually lower than the indoor temperature). The impact of envelope renovation measures is further addressed in this study as an indirect impact of climate change on building energy demand (considering that the proposed building renovation policies act as climate change mitigation measures).

Aside from the fact that the combined effect of direct and indirect impacts could affect different building design strategies for achieving the required energy efficiency (Cao, Li, Wang, Xiong, & Meng, 2017; European Parliament, 2010; Hosseini, Tardy, & Lee, 2018), these factors could have an impact on the design and development of urban energy systems (i.e. district heating and cooling systems, DHCSs). These systems are commonly proposed in the literature (Andrić, Pina, Ferrão, Lacarrière, & Le Corre, 2016; Connolly, Mathiesen, & Østergaard, 2012; Lund et al., 2014; Persson & Werner, 2011) as an environmentally friendly solution for providing heating and cooling services for the built environment due to their multiple benefits including centralized heat production located outside city centres, large-scale utilization of renewable heat sources (solar, geothermal, etc.) and waste heat, overall environmental and economic efficiency, along with comfort and supply security for consumers.

New construction of DHCSs and the expansion of existing systems has been widely proposed in multiple scientific and governmental reports (Connolly et al., 2012; Dominković et al., 2017; European Comission, 2012, 2016; Gils, 2012; Grundahl, Nielsen, Lund, & Möller, 2016; Lund et al., 2014; Rezaie & Rosen, 2012; The Scottish Government, 2014). However, these systems have significant investment costs due to the amount of infrastructure that needs to be placed and physical obstacles to be crossed. The initial investments are intended to be recovered through heating and/or cooling sales over a generally long return period. Therefore, the feasibility of such projects is highly sensitive to changes in future building energy demand. Furthermore, these impacts could significantly prolong the investment return periods for DHCSs and affect their operational parameters (Andrić, Fournier, Lacarrière, Le Corre, & Ferrão, 2018). For example, if the future heating base load decreases, heat production units will run with lowered capacity, and thus reduced efficiency. Additionally, a decrease in heating hours during the year would cause frequent starts and stops in heat production, further decreasing the efficiency of heat production units and increasing their fuel consumption (consequently increasing operational costs). On the other hand, an increase in cooling demand and the number of hours with cooling demand would cause an overload of the base load and peak load units, making the initial system design obsolete. Consequently, the evaluation of building energy demand under future climate change conditions is currently one of the most relevant aspects for building energy efficiency policy makers and district energy utilities.

Thus, in order to ensure the sustainable development of the urban environment in the future, sustainability measures and mitigation policies should be evaluated for the future climate and state of the building stock, rather than the current one. The performance of building renovation measures and the feasibility of urban district systems in previously discussed reports were evaluated based on the past and current weather conditions, while the performance under the future conditions was frequently overlooked. However, estimating the direct and indirect impacts of climate change on urban environment and associated energy systems is a complex and daring endeavour. The development of adequate methodology and qualitative and quantitative analysis of results requires an interdisciplinary background (knowledge of both climate and building models, as well as familiarity with environmental impact assessment and mitigation policies). Additionally, the uncertainty of such models presents an additional challenge.

The main scope of this study is to provide an up-to-date review of comprehensive approaches developed for the assessment of future building heating and cooling energy demand and consequent implications for the urban environment. The focus of the study is not the comparison of tools used for building energy simulations, which has been elaborately discussed within the existing bibliography (Crawley, Hand, Krummert, & Griffith, 2005; Wang & Zhai, 2016; Harish & Kumar, 2016; Li et al., 2017), but rather on the methodology for the building energy forecast as a whole (combination of different tools and methods and their suitability for a large-scale application and long-term forecast). Previous research efforts from the bibliography are assessed, highlighting their key purposes, strengths, and limitations. Each study has been evaluated based on the complexity of the climate and energy demand models used, the case study scale, and the ability to account for both direct and indirect climate change impacts, along with climate type variation. Additionally, by comparing the results from these studies, potential implications for the design of building envelope elements and district energy systems are assessed. Finally, the uncertainty levels in the methodologies used are quantified.

Review methodology

In order to assembly and categorize appropriate peer-reviewed bibliography in English, previously developed approach by the authors was used (Mannan, Al-ansari, Mackey, & Al-ghamdi, 2018; Raouf & Al-Ghamdi, 2018), where the literature search process was adopted from the study of Geissdoerfer, Savaget, Bocken, and Hultink (2017), while the methodology outline and description are analogue to the studies of Le Hesran, Ladier, Botta-Genoulaz, & Laforest, 2019; Prasara-A & Gheewala, 2018.

Literature search

The search for publications relevant to the topic discussed covered all major subscription-based research databases and citation indexing services such as Scopus, Web of Science, EI Compendex, Science Direct, Research Gate and Google Scholar, and was conducted in May 2018. Among these sources, Scopus is the largest abstract and citation database of peer-reviewed literature (covers nearly 36,377 titles from approximately 11,678 publishers, of which 34,346 are peer-reviewed journals) and was consequently used as a primary source in this study. Additionally, the comparative analysis of Gavel and Iselid (2008) concluded that there is a significant match between the citation search results from the Scopus and Web of Science databases. In order to ensure that relevant publications are not missed, major publisher databases were also searched individually (Taylor & Francis, Elsevier, Wiley & Sons, ACS Publications, IOP Science and American Society of Civil Engineers (ASCE)). In this review, the classification of studies reviewed is presented based on the publisher rather than scientific database, due to the fact that several studies have indicated the overlap between databases and the impact of using different data sources for specific research fields on bibliometric indicators (Aznar-Sánchez, Belmonte-Ureña, Velasco-Muñoz, & Manzano-Agugliaro, 2018; Mongeon & Paul-Hus, 2016).

Screening process and selection of the literature

The initial search based on several combinations of keywords was conducted in July 2018, and the search process was done in accordance with the approach previously suggested within the bibliography (Creswell, 2009; Denyer & Tranfield, 2003). Initially, the following keywords were used: 'climate change', 'buildings', 'architecture', 'impact', 'modelling'. After the initial search, additional keywords were selected to narrow the search on climate change impacts on building energy demand ('heating demand', 'cooling demand'). Second search was added to cover the literature addressing the impacts on urban energy systems related to buildings ('climate change', 'impact', 'district heating' and 'district cooling'). Furthermore, in order to quantify the uncertainty of such modeling approaches, an additional search was conducted by using the following keyword group: 'climate change', 'models', 'uncertainty', 'precision'. Based on the abstract evaluation, the initial sample of relevant papers was selected, which was used for cross-reference search (Figure 1).

In general, the studies identified by the previous steps either directly considered the change in heat transfer rate between the building and environment, or expressed energy demand evolution as a function of other non-physical parameters (such as potential changes in economic parameters, population increase, and migration, etc.). However, the potential issue with expressing building energy demand evolution without modeling heat transfer between the building and environment could exist in sampling errors, construct validity, and correlation-versus-causation problems. Thus, in this review, only modeling approaches that in some form took into account heat transfer through the building envelope or measured building energy consumption data were considered. Additionally, studies that focused on evaluating the impact of the heat island effect (the difference in air temperature between rural and urban areas) were also excluded from consideration, due to the fact that changing air temperature in urban settings is caused by the growth and agglomeration of the urban environment and the materials used for urban infrastructure, rather than climate change itself. Moreover, since the focus of this study was on modeling approaches for the creation of future conditions, studies that evaluated building energy consumption trends for previous decades (1950s–2000s) were also excluded from this review. Furthermore, since the search results included publications on the topics that

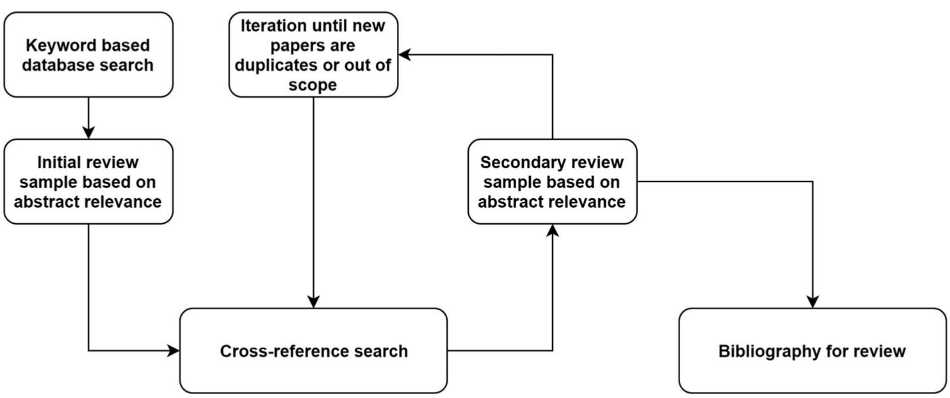

Figure 1. Review database selection process (adapted from Geissdoerfer et al., 2017).

were out of the main scope of this study (such as building environmental impact, the impact of climate change on building structure through floods etc.), such studies were excluded from this review. Iteration was performed until newfound papers were not contributing significantly to the research question addressed in this review. Finally, duplicates were removed: in the case that research material was published in both conference proceedings and a journal, only journal publication was considered (within this study, Elsevier's *Energy Procedia* was treated as a journal). The same principle was applied for thesis material and journal publications. After the application of the filters described, the search resulted in 79 studies that comprise the core of this review. Table 1.

Modelling the climate change impacts

According to the initial bibliography survey, modelling of climate change implications for architecture consists of following steps (Figure 2):

- Definition of climate change impacts considered (direct and/or indirect)
- Development of weather and building renovation scenarios
- Building energy modelling
- Estimation of heating and cooling demand evolution
- Climate zone variation

Each of these steps is discussed in detail within the following sections, and an overview of the modelling approaches used by the studies available in the bibliography to conduct these steps is given in Table 2.

Climate change impacts considered

Concerning the impacts of climate change studied, only 17 of 45 studies (Table 2) considered the combined effect of direct and indirect impacts of climate change, while the rest of the studies addressed solely the direct impact (the effect of changed weather

Table 1. Review pool classified by the publisher/type.

Publisher/ Keywords used	Climate change, architecture, buildings, impact, modelling, heating demand, cooling demand	Climate change, district heating, district cooling, urban energy systems, impact	Climate change, modelling, uncertainty, precision
Taylor & Francis	5	–	1
Elsevier	41	5	2
Springer	2	1	5
Wiley & Sons	1	–	1
Science			2
World Scientific	1	–	–
Independent publishing*			8
Governmental agencies report	1	–	–
Conferences	1	2	
Theses	–	–	–
Book chapters	–	–	–

*in this group, we have categorized peer-reviewed papers from independent agencies, such as National Academy of Sciences, American Meteorological Society, etc.

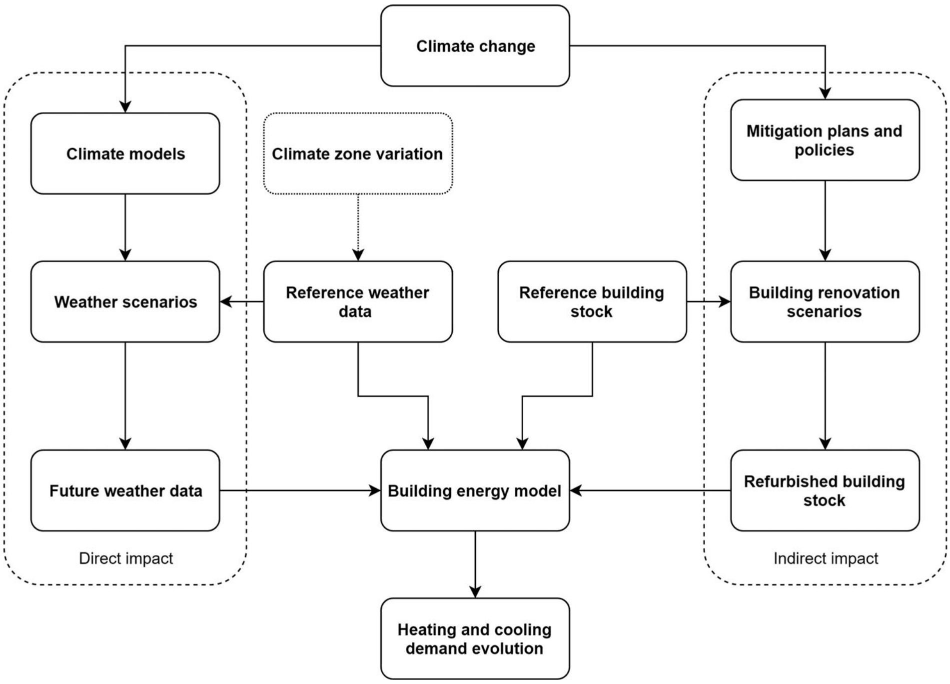

Figure 2. General overview of the modelling approaches.

variables). Based on climate change predictions from scientific reports (such as the IPCC Fifth Assessment Report (IPCC, 2014)) and upcoming building renovation polices (i.e. as defined in the EPBD directive), it seems relevant to account for both impacts in order to assess future building energy demand evolution. Moreover, the findings from the studies reviewed in this paper suggested that indirect impact (modifications in building envelope thermal performance) could have significantly higher impacts on building heat demand in the future, while the changed weather variables had more significant impacts on cooling demand. For example, the case study for Lisbon (Andrić et al., 2016) indicated that when solely direct impact was considered, predicted heat demand decrease was varying within the 1.7–9.3%, while when both impacts were considered, the maximum demand reduction was 52%. Nevertheless, the majority of studies suggested that the envelope renovation measures should be carefully designed, taking into account local climate properties (i.e. the ratio between heating and cooling demand) and potential changes in climate conditions. The development of both weather and building renovation scenarios is discussed in more details in the following section.

Development of weather and building renovation scenarios

In order to account for both direct and indirect climate change impacts and assess the building energy demand in the future, two types of scenarios should be developed: weather and renovation scenarios. Under weather scenarios, future weather variables that have a major impact on building energy demand (outdoor air temperature, solar radiation, humidity, wind speed) should be forecasted based on historical weather

Table 2. Overview of the reviewed studies addressing the impact of climate change on building energy demand.

	CLIMATE CHANGE IMPACTS		ENERGY DEMAND MODEL		ENERGY DEMAND ASSESSED		CASE STUDY		CLIMATE VARIATIONS	
STUDY REFERENCE	*Direct*	*Indirect*	*Complex[a] model*	*Simple model*	*Heating demand*	*Cooling demand*	*Representative buildings(s)*	*Building stock[b]*	*In-country*	*Global/ regional*
Frank, 2005	x		HELIOS		x	x	x			
Radhi, 2009	x	x	Visual DOE		x	x	x			
Crawley, 2008	x		Energy Plus		x	x	x			x
Isaac & van Vuuren, 2009	x			From IAEA	x	x		x		x
Dolinar, Vidrih, Kajfež-Bogataj, & Medved, 2010	x		TRNSYS		x	x	x		x	
Wang et al., 2010	x		AccuRate		x	x	x		x	
Olonscheck et al., 2011	x	x		By the authors	x	x		x		
Xu, Huang, Miller, Schlegel, & Shen, 2012	x		DOE-2.1E		x	x	x		x	
Nik & Sasic Kalagasidis, 2013	x		By the authors[c]		x	x	x			
Berger et al., 2014	x		TAS		x	x	x			
Nik et al., 2015	x	x	By the authors		x		x			
van Hooff, Blocken, Timmermans, & Hensen, 2016	x	x	Energy Plus		x	x	x			
Nik, Mata, Sasic Kalagasidis, & Scartezzini, 2016	x	x	By the authors		x		x		x	
Fazeli, Davidsdottir, & Hallgrimsson, 2016	x			By the authors	x			x		
Rubio-Bellido et al., 2016	x		By the authors		x	x	x		x	
Huang & Hwang, 2016	x	x	Energy Plus			x	x			
Shibuya & Croxford, 2016	x	x	TAS		x	x	x		x	
Andrić, Gomes, et al., 2016	x	x	By the authors		x			x		
Shen, 2017	x		Energy Plus		x	x	x		x	
Sabunas & Kanapickas, 2017	x		HEED		x	x	x			
Wang, Lin, et al., 2017	x		Energy Plus		x	x	x		x	
Andrić, Pina, Ferrão, Fournier, et al., 2017	x	x	By the authors		x		x			x
Andrić et al., 2018	x	x	By the authors		x			x		
Zhou, Eom, & Clarke, 2013	x			By the authors	x	x	x			
Angeles, González, & Ramírez, 2017	x			By the authors	x	x	*			x
Xiang & Tian, 2013	x		TRNSYS		x		x			
Vidrih & Medved, 2008	x		TRNSYS		x	x	x		x	
Jiang et al., 2017	x		Energy Plus		x	x	x		x	
Andric et al., 2014	x		By the authors		x			x		

Andrić et al., 2015	x	x	By the authors	x			x		
Yau & Hasbi, 2017	x		TRNSYS		x	x			
Wang, Liu, et al., 2017	x		Energy Plus	x	x	x		x	
Nik & Arfvidsson, 2017	x		By the authors	x		x			
Invidiata & Ghisi, 2016	x	x	Energy Plus	x	x	x		x	
Wang & Chen, 2014	x		Energy Plus	x	x	x		x	
Tettey, Dodoo, & Gustavsson, 2017	x	x	VIP-Energy	x	x	x			
Waddicor et al., 2016	x	x	IDA ICE	x	x	x			
Ouedraogo et al., 2012	x	x	IES VE		x	x			
Roshan, Orosa, & Nasrabadi, 2012	x		By the authors	x	x	*		x	
Wan, Li, Liu, & Lam, 2011	x	x	DOE-4.1	x	x	x		x	
Guan, 2009	x		DOE-2.1E		x	x		x	
Guan, 2012	x	x	DOE-2.1E		x	x		x	
Dodoo, Gustavsson, & Bonakdar, 2014	x		VIP+	x	x	x			
Pilli-Sihvola, Aatola, Ollikainen, & Tuomenvirta, 2010	x		By the authors	x	x	*			x
Jylhä et al., 2015	x		IDA ICE	x	x	x			

[1]According to the ISO 13790:2008 standard, complex dynamic models should be able to account for thermal inertia and variations in hourly heat gains/losses
[2]Building stock on a neighbourhood (500+ buildings), city, national, or global scale
[3]the term 'By the authors' indicates that the model used was developed by the authors of the study
*instead of performing simulations for a representative building, building energy demand was calculated through heating and cooling degree days.

observations (reference building data) and theoretical models for the future (Figure 2). Renovation scenarios consider changes in the building envelope due to the new building energy efficiency policies. Such scenarios should consider the current state of the building stock and its properties, available renovation measures, existing policies, as well as the sustainability goals set (Figure 2).

For the creation of weather scenarios, most studies (42 of 45) used the approach of morphing the typical meteorological year data with downscaled output data from Global Circulation Models (GCMs) or regional climate models, while the remaining three studies created future scenarios based on the recorded temperature increase over previous decades. The credibility of GCM output is limited (which will be discussed in detail later on), especially when the focus is on finer scales: an increase in model resolution generates more spatial details but not necessarily more accurate weather predictions, since the sub-continental-scale model performance remains poor (as elaborated by Hargreaves & Annan, 2014). However, the development and operation of regional GCMs is financially, computationally, and time consuming, with only a handful of research centres being able to afford supercomputers and such model development. Thus, it seems that downscaling and morphing the weather data from GCMs to the case study scale currently remains the only feasible option for most researchers, although the impact of climate prediction uncertainty should be considered through sensitivity studies. The most popular morphing tool among the studies proved to be the CCWorldWeatherGen tool, developed by a research group from the University of Southampton (Jentsch, James, Bourikas, & Bahaj, 2013).

Regarding the renovation scenarios for representative buildings, the majority of studies considered solely the modifications in insulation levels of building envelope elements (walls, roofs, and floors) and the installation of more energy efficient windows, while some studies included changes in building architectural design (the addition of solar shading/overhangs and green roofs). In order to forecast building envelope thermal performance parameters (i.e. U-values of envelope elements after renovations), all studies relied either on previous publications and/or energy efficiency reports from the case study location, or global reports from the International Energy Agency. However, upscaling the renovation measures to a building stock scale presented a challenging task. Out of the five studies that considered building renovation on a large scale, three (Andrić, Pina, Ferrão, Fournier, et al., 2017, 2018; Olonscheck, Holsten, & Kropp, 2011) considered uniform renovation scenarios (the same scenario applied for the whole building stock), while two (Andrić et al., 2015; 2016) considered the relationship between various building selection parameters for renovation: position within the observed building stock, level of renovation, renovation depth (i.e. the number of buildings selected based on the other two criteria that were actually renovated). However, these criteria were obtained from the E.U.-scale report (Building Performance Institute Europe, 2011), which presents an average for all member countries.

Considering that the building stock may vary significantly from one country to another, the optimum solution would be to develop building stock renovation criteria based on specific data from the case study country's building stock. In recent years, multiple countries have published publicly available strategies for building stock renovation in both their native languages and English, such as Germany (Building Performance Institute Europe, 2015), Bulgaria (Building Performance Institute Europe, 2016), and Romania (Building Performance Institute Europe, 2014). Moreover, there are several reports available (Building Performance Institute Europe, 2013; Building performance Institute Europe, 2014b) that summarize the best practices for conducting such renovation on a large scale; these could potentially be used to develop renovation scenarios for countries where such reports are not yet available. Some of these practices include the collection of accurate building stock data, the creation of dynamic building codes, and the introduction of stable and predictable policies and frameworks. Additional efforts could be invested in order to create accurate building databases which would serve as the basis for the renovation policy definition. Each municipality could collect the data for its building stock from the contractors that were involved in the construction process, and deliver it to city governance planning & housing division which could coordinate the data aggregation with national energy agencies. Scientific community could contribute to these efforts by performing analysis on the existing databases and conducting combination of empirical and theoretical studies in order to define building archetypes, as it was case in the studies of Csoknyai et al., 2016; Johansson, Olofsson, & Mangold, 2017; Magalhães & Leal, 2014; Monteiro, Costa, Pina, Santos, & Ferrão, 2018; Monteiro, Pina, Cerezo, Reinhart, & Ferrão, 2017 and Österbring et al., 2016. For example, the combination of remote sensing and GIS (Geographic Information Systems) proved to be successful in the building stock data collection process (Santos et al., 2014). Thus, it would be desirable for future studies that consider large scale building renovation scenarios to take into account recommendations from Building Performance Institute Europe and national reports, as well as results from the research studies already available within the bibliography.

Building energy demand models used

With regard to building energy modeling, most studies (38 of 45) considered a representative building(s) as a case study. These authors defined the most characteristic building type(s) for their case study location (based on relevant criteria) and then performed energy consumption simulations, taking into account future weather scenarios. In most cases, the main criterion for a representative building selection was based on the recurrence level of certain building type(s) within the observed urban environment (either geographically clustered building stock or buildings grouped based on the type (residential, commercial etc.) and/or construction period). However, the urban environment usually consists of various building types originating from different construction periods that can differ drastically in both size and geometry. Thus, upscaling the heat demand for a whole district or city based on a calculation for representative building(s) could provide misleading results.

All such studies used complex simulation models in order to calculate heat demand, with Energy Plus being the most commonly used software; this is understandable considering its open-source nature and the vast quantities of weather data available in its online database. On one hand, simulating energy demand for a specific building with complex simulation software enables dynamic simulations with detailed building input data. On the other hand, modeling large number of buildings in this manner consumes large amounts of both time and computational power. Thus, most studies that addressed building stock simulations on a large scale used simplified models or building energy consumption data based on statistical reports.

Modeling the demand based on statistical data is a faster approach compared to complex simulations with commercial software, but the simulation dynamics are on a low level. For example, energy demand for multiple buildings is often estimated based on the simulation of one building with similar properties (usually expressed as $kWh/m^2/yr$), without the ability to provide an adequate demand profile on an hourly basis that accounts for thermal inertia, changes in hourly gains/losses, etc. One study (Andrić et al., 2016) developed a model with similar characteristics, but solely for heat demand calculations since the research focus was on the implications for traditional urban heating systems, which contrary to the new generation of urban energy systems, only provide heating services. However, if the main scope of the study is to evaluate climate change impacts on total building energy demand, it is imperative that both heating and cooling demand are taken into account.

While this aspect is of utter importance for temperate climates, where the share of heating and cooling demand in total building energy consumption is almost equal, in climates with severe conditions where heating or cooling demand is prevalent (over 90% of the share), it is understandable to consider only heating/cooling demand (as in the case studies for Burkina Faso (Ouedraogo, Levermore, & Parkinson, 2012), Taiwan (Huang & Hwang, 2016), and the U.A.E. (Radhi, 2009)). The methods developed by Mata, Kalagasidis, and Johnsson (2013) and later used in by Nik, Mata, and Kalagasidis (2015) and Nik and Sasic Kalagasidis (2013) also seem to fit the required description, but the model itself was not applied to a case study that accounted for all relevant factors (direct and indirect impact, large scale building stock, climate differences, etc.). Thus, it appears that there is an existing need for the development of a dynamic building energy demand model that is capable of dynamic heating and cooling demand calculations on a large scale (for the building stock at the neighbourhood, city, or possibly national level), but without significant calculation time or computing power. However, such model should be able to take into account all relevant building properties (geometry, thermal properties, occupancy profiles, etc.) and be capable of accounting for different future weather and building renovation scenarios. Consequently, editing the input weather data (for different locations and weather scenarios), as well as building data (for building reference state and renovation scenarios) should not be a complicated and time-demanding process for such a model.

The evolution of building heating and cooling demand

As for the impacts assessed, it is rather difficult to compare all studies and results from the bibliography on an equal basis. The studies considered different locations, time horizons, and climate change impacts, while using weather and building data that was not always publicly available (especially in the case of large-scale studies). However, general observations can be made based on the studies in which time horizons included the same year for future scenarios, and which compared the future demand with pre-2020 levels. Within the studies presented in Table 2, the most common year in the scenarios for heating demand estimation was 2050, while in the case of cooling demand estimations, year 2080 was most commonly considered. The results from these studies are presented in Figure 3 (heating demand evolution) and Figure 4 (cooling demand evolution). It can be

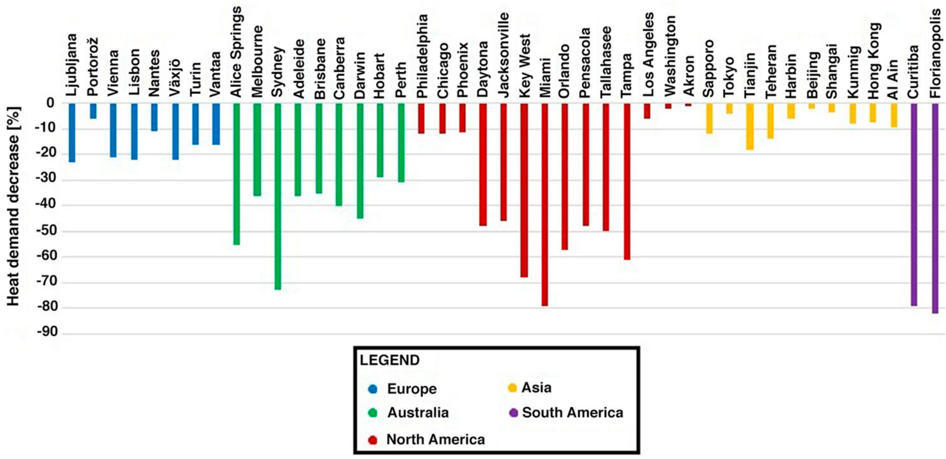

Figure 3. Projected heat demand decrease for 2050 based on the studies presented in Table 2.

observed that in both cases, locations with warm climates were most sensitive to climate change impacts on building energy demand. For example, heat demand in the case study (Invidiata & Ghisi, 2016) for Curitiba and Florianopolis (Brazil), as well as in case study (Jiang, Zhu, Elsafty, & Tumeo, 2017) for multiple cities located in Florida (United States) decreased on average for 80% and 75%, respectively. Similar trends were obtained for other locations within the warm climates considered (please refer to Figure 1). On the other hand, the forecasted trend in cooling demand for these locations varied more

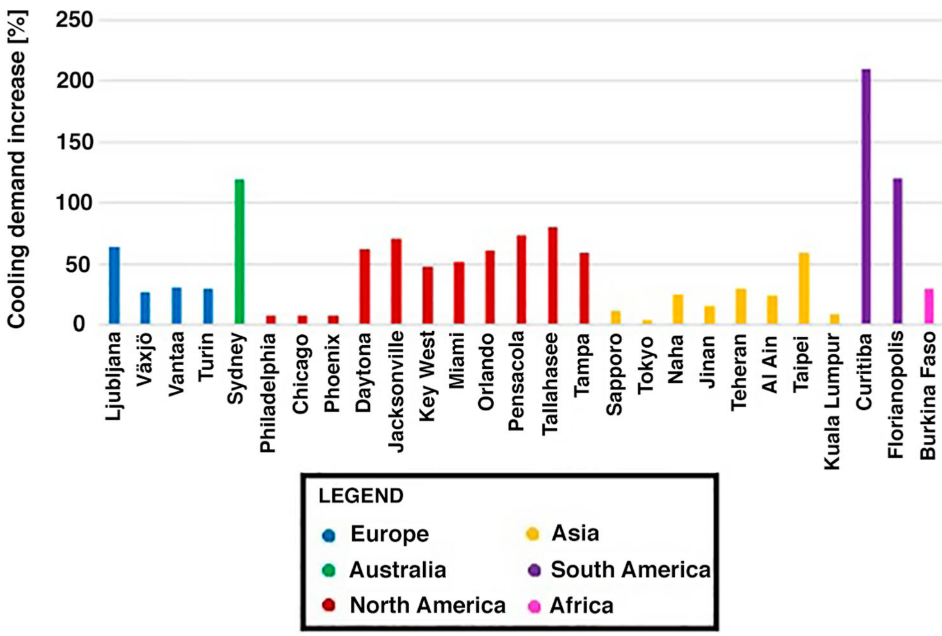

Figure 4. Projected cooling demand increase for 2080 based on the studies presented in Table 2.

significantly (for the cities situated in Florida, predicted cooling demand increase varied between 48 and 80%, while in the case of the two Brazilian cities considered, the results suggested an increase of up to 210% compared to the reference conditions (pre-2020)), in spite of having fairly similar warm and humid climates. To further investigate the relationship between climate properties and forecasted trends, the second group of studies that had the second most common year in scenarios for cooling demand forecast (2050) was compared, and it was found that the predicted increase rates in cooling demand varied significantly, from 1 to 1050% in 2050 compared to the reference levels.

At first glance, it could seem that local climate properties did not seem to impose a major correlation: for example, in a case study of Switzerland (which has moderate climate conditions), predicted cooling demand increase ranged from 223 to 1050% (Frank, 2005), while in case studies of Taiwan (Huang & Hwang, 2016) and the U.A.E. (Radhi, 2009), which have hot climates, increase rates were 59% and 24%, respectively. In order to obtain a more detailed insight into the variance between the increase and decrease rates, studies that represented the results in form of total building energy consumption and heating/cooling demand ratio (Invidiata & Ghisi, 2016; Shen, 2017; Shibuya & Croxford, 2016; Wang, Chen, & Ren, 2010) were further analysed. The analysis indicated that the initial heating/cooling demand ratio in reference weather conditions has a major role in practical meaning of increase rates. Even with the lower cooling demand percentage increase than the heating demand percentage increase, building overall energy demand increases in warmer climates. In other words, for the reference weather conditions in warm climates, heating demand is relatively small compared to cooling demand. For example, in the case study for Tokyo (Shibuya & Croxford, 2016), building energy demand in 2050 increased for 13% after the heat demand decrease of 263% and cooling demand increase of just 17% (for the reference weather conditions, heating/cooling demand ratio was 5%/95%). Similarly, in the case study (Shen, 2017) for Phoenix (Arizona, United States), the result indicated that total building energy demand will increase for 7% in 2050 after the 49% decrease in heating demand and 24% increase in cooling demand. Both locations had warm, cooling dominant climates – humid subtropical (Tokyo) and hot desert climate (Phoenix). Vice-versa is true for temperate and cold climates – heating demand is significantly higher than cooling demand, and higher percentage decrease in heating demand compared to cooling demand does not necessarily result in reduced overall building energy consumption. This can be observed in the case of Hobart (Australia) with temperate oceanic climate (studied by Wang et al., 2010), where the reduction of heating demand of 26% and increase in cooling demand of 173% resulted in total building energy decrease (26%). Going back to the previously mentioned studies and increase rates for Switzerland (Frank, 2005) and U.A.E. (Radhi, 2009), cooling demand in Switzerland was lower than 3kWh/m^2/yr under the reference conditions and increased up to 70kWh/m^2/yr after the application of weather scenarios, while the reference cooling demand in the U.A.E. was 176kWh/m^2/yr, which explains the large discrepancy in the cooling percentage increase rates (223–1050% for Switzerland and 24% in the case of U.A.E.).

Considering that the majority of studies used the same methodology for the creation of weather scenarios, it can be argued that the selection of case study buildings (i.e. their thermal performance), scenarios developed and time horizons considered, as well as building energy simulation tools used had a major impact on the results. For example, two studies in the bibliography (Guan, 2012; Wang et al., 2010) considered same locations in Australia as case studies (Darwin, Hobart, Melbourne, and Sydney), and yet obtained different results in their forecast. The study of Guan suggested an increase of approximately 12% in total building energy demand, while the results of Wang et al. indicated an increase of approximately 80%. For certain cities, even the trend was opposite – for Hobart and Melbourne, Guan predicted an increase in building energy demand (6% and 9% respectively), while Wang et al. suggested a decrease of 22% and 18% (respectively). The difference can be justified by the fact that the authors used different approaches for climate and building energy modelling, as well as different building types (single family house and office building), which also have different construction properties and thus envelope thermal performance. Analogue conclusion can be made by comparing the studies for Miami and Phoenix by Shen (2017) and Wang, Liu, and Brown (2017).

Thus, due to the high level of variables between the case studies for different (or even same locations in certain cases), in order to enable the comparison of study results on the same basis, the authors should provide a detailed representation of the input data, related sources, assumptions taken and key performance indicators used to assess the results obtained. Based on the modelling approaches reviewed in this paper, future studies should clearly state:

- Reference weather parameters for the case study location
- Reference building state (i.e. U-values of the building envelope elements, occupancy, heat gains, etc.)
- Building energy demand for the reference state and the ratio between the heating and cooling demand (in kWh/m^2/yr)
- Studied time horizon for the scenarios
- Forecasted weather parameters for the scenarios considered
- Forecasted building envelope thermal performance after the application of renovation measures
- Building energy demand for the future conditions and the ratio between heating and cooling
- Whether the results obtained were interpreted as energy demand or energy consumption, or provide a conversion factor used (i.e. energy efficiency of the heating/cooling system used in order to account for losses and the gap between energy demand and energy actually consumed).

The two previously discussed studies (Guan, 2012; Wang et al., 2010) can be used as a good example of representing all these aspects. Considering the number of different global and regional climate types, as well as different building types, the provision of results on an equal and consistent basis could enable researchers and policy makers to better understand and compare climate change impacts on the building sector and devise efficient strategies for improving the sustainability of the urban environment.

Climate variations considered

The results from 22 studies that accounted for climate differences highlight the relevance of studying climate change impacts on heating and cooling demand in different climates, especially in countries that cover multiple zones according to the Köppen climate classification. For example, variations in heating/cooling decrease/increase rates ranged from 10/60% in Australia (Wang et al., 2010) and 25/20% in the U.S. (Shen, 2017) depending on the area studied. The country's size does not seem to have as much influence as its location. For example, case studies for Chile (Rubio-Bellido, Perez-Fargallo, & Pulido-Arcas, 2016) and Japan (Shibuya & Croxford, 2016) also showcased notable variations between the energy demand decrease/increase rates, although their overall land surface is approximately 12 and 26 times smaller (respectively) than the U.S. and China. However, due to its shape, Chile stretches over 4300 km from 17° to 56°S, encompassing a remarkable variety of climates and landscapes; a similar pattern exists for Japan. This factor should be taken into consideration when developing national building renovation scenarios (as well as policies), as different regions within a given country could require different renovation measures and strategies. Classification and the definition of climate zones and representative locations for building energy simulation relative to the climate change impacts, buildings and energy systems studied could enable the comparison of the results on a same basis. Representative climates and locations for the evaluation of climate change impacts on building energy demand were developed by Andrić, Pina, Ferrão, Fournier, et al. (2017) based on the initial findings of Mansy (2006). However, the study tried to define representative locations solely for the climate change impacts on building heat demand (taking into account heating-dominated climates), which left the research gap related to building cooling demand, which should be addressed in future studies.

Uncertainty quantification

In the previous sections, the approaches used for the initial approximation of climate change on the architecture were discussed, as well as the preliminary results obtained. However, in every modelling approach where it is difficult to validate the results with adequate experimental data, the certainty and precision of the results could be questioned. In the case of climate change impacts estimation, the uncertainty is even higher, since multiple assumptions are made while using a combination of different sets of models on different scales. As indicated in the editorial comment of El-Nawawy and Mohamed (2012), the level of uncertainty gradually increases during each step from the prediction of emission scenarios towards quantifying the range of possible impacts (Figure 5). In the particular case of evaluating the climate change impact on building energy demand, the uncertainties can be presented as in Figure 6. Two types of uncertainty can be observed: probability and precision. The probability issues are related to prediction of future events that could affect the results, while precision is related to the accuracy of the models used.

The majority of uncertainties related to probability are related to climate change prediction and development of adequate mitigation measures and policies. While overwhelming proofs of climate change have been presented over the previous three decades, climate change as a process is still questioned, with several sceptics declaring climate change as a 'deception' and that the climate change effects have been overestimated (Mansel, Waight, & Sharkey, 2013). Oddly, since the release of the third IPCC assessment report in 2007 and the increase in quantity, quality as well as diversity of credible scientific information proving the climate change, such claims have become more

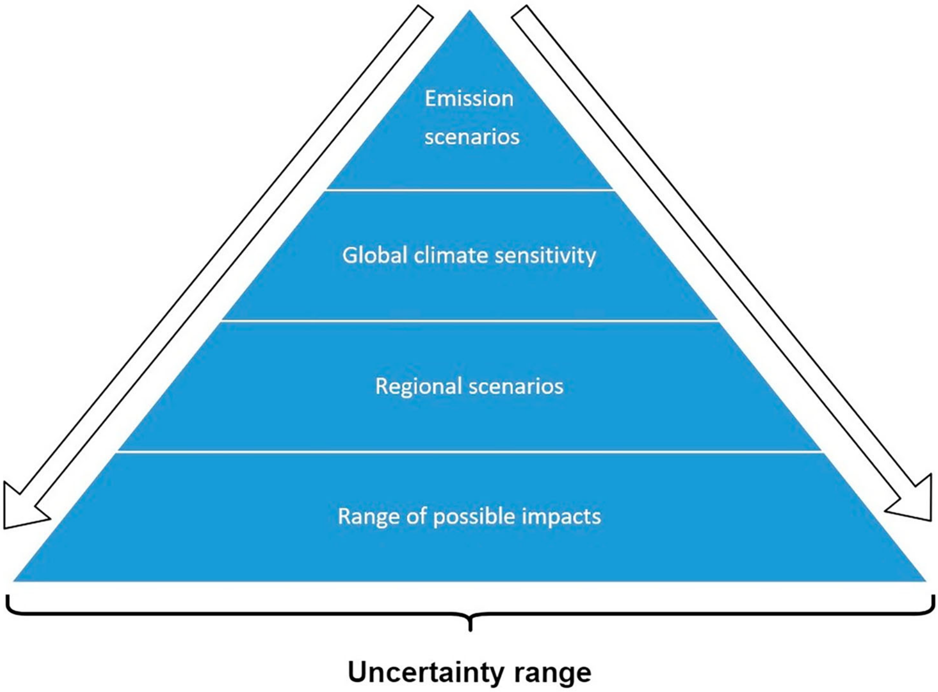

Figure 5. Uncertainty range increase in climate change impact assessment according to El-Nawawy and Mohamed (2012).

common (Mansel et al., 2013). Nonetheless, later IPCC reports proved that the initial projections were not exaggerated, but in some aspects even underestimated. Furthermore, it is extremely likely that many climate change-driven changes in natural environment will be irreversible (Heal & Kriström, 2002). However, while it has been proved that climate change is an ongoing process, climate change predictions are still uncertain, due to the unknown future concentrations of greenhouse gasses and other relevant anthropogenic and natural forcing agents (Collins et al., 2006; Hawkins & Sutton, 2009). The second probability issue is related to building renovation plans and policies. For example, the study from Building Performance Institute Europe found that despite more than 20 years of continuous efforts in building energy efficiency legislation, the legislative context has remained weak for the existing building stock that should be renovated (Building performance Institute Europe, 2014a). Additionally, based on the evaluation of national renovation plans for ten countries, the study found that they had a low level of compliance with the originally suggested requirements by the E.U. directives (Building performance Institute Europe, 2014b). For example, in the U.K., in order to achieve the sustainability goals set, about 600,000 homes should be renovated each year, while in reality, less than 1000 homes are refurbished each year (Fawcett, Killip, & Janda, 2011). Taking into consideration that building renovation scenarios are mostly based on current directives and renovation plans, and the previously discussed potential inaccuracies in reference building data collection for the definition of representative building stock, actual building stock properties in the future may differ from predictions. However, since in recent years the efforts related

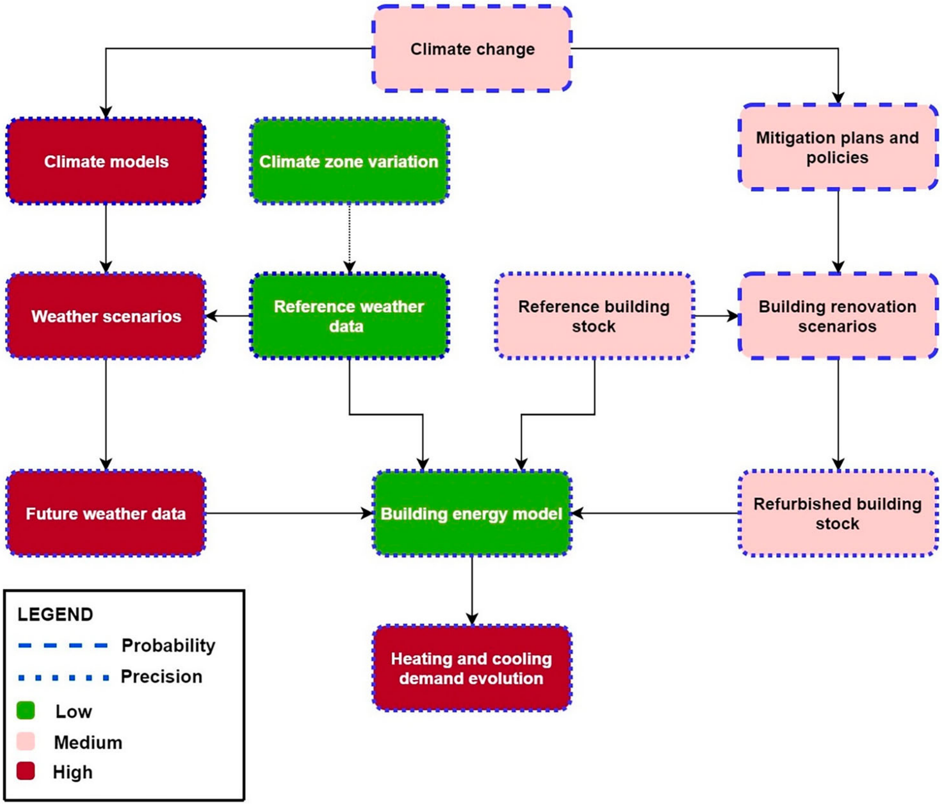

Figure 6. Uncertainty assessment.

to climate change mitigation and policy development are increasing, the risk of such probability uncertainties and precision errors can be assessed as medium.

The lowest uncertainty risks are related to reference weather data collection and the precision of building energy models used. Typical Meteorological Years commonly used as a reference state are derived from the weather data recorded over the previous two to four decades. By including the simulations for different climate zones within a certain country, the authors simply use TMY for different locations, which does not influence the uncertainty of the results, as long as the locations and climate zones studied are clearly stated, and climate properties elaborated. In regard to the building energy models used, the majority of the authors used either a commercial software (such as TRNSYS, Energy Plus, Helios, IDA ICE etc., which was validated in the bibliography on multiple occasions), or developed a new model (which was then calibrated and validated through the comparison with commercial software and/or measured data). Thus, it can be considered that the uncertainty risk related to precision of such tools is fairly low.

On the other hand, the highest risk of precision uncertainty comes from climate models and consequently developed weather scenarios and resulting future weather parameters. While the GCMs have an increasing ability to successfully model the current weather conditions, even the latest generation of models has significant difficulties in reproducing parameters such as daily precipitation and temperature (Semenov & Stratonovitch, 2010; Trigo & Palutikof, 2001). The potential errors arise from missing, poorly-resolved or structurally defective representations of physical processes, due to which during model tuning and calibration a balance can be achieved for the wrong reasons (Collins et al., 2006). Additionally, limitations in computing power and understanding of small-scale processes, along with the lack of detailed observations necessary for model validation presents an additional challenge (Semenov & Stratonovitch, 2010). Moreover, climate models are usually tuned to resemble the current climate properties, simply due to the mathematical constraint: parametrization schemes that are utilized for the characterization of unresolved processes include numerical constants which cannot be deduced accurately based on theoretical nor process-level observations (Räisänen, 2007). However, GCMs and associated models are constantly developing and improving through comparisons with observed weather changes, which should increase the forecast precision and reduce the uncertainty (Palmer, Doblas-Reyes, Hagedorn, & Weisheimer, 2005; Semenov & Stratonovitch, 2010). Moreover, the models are routinely intercompared (Covey et al., 2003; Déqué et al., 2007; Huebener et al., 2007; Jacob et al., 2007; Semenov & Stratonovitch, 2010), which enables their unbiased assessment and expands the opportunities for their improvement. Additionally, the improvements in the regional climate model's ability to simulate spatial weather patterns at fine spatial resolution between 25 km and 50 km should further improve the forecast precision (Beniston et al., 2007; Salon et al., 2008; Semenov & Stratonovitch, 2010).

Even with low uncertainty associated with building energy model precision, there is a high level of uncertainty for the final impacts assessed (due to the medium risk of precision with forecasting the future state of the building stock and high uncertainty risk of predicted weather data). An additional limitation is the fact that probability is rarely assigned to the climate change scenarios by the experts. Even in the rare cases where the probability is assigned, the suggested range is still very high (Heal & Kriström, 2002). For example, the widely acknowledged suggested range (1.5–6°C) for the evolution of global mean temperature in IPCC reports recognizes multiple confidence levels for the scenarios: very high ($\geq 95\%$), high ($67 \leq X \leq 95\%$), medium ($33 \leq X \leq 67\%$) and very low ($\leq 33\%$). The effect of such uncertainty can be observed in the heating and cooling demand decrease/increase rates suggested by the case studies reviewed in this paper, where the range presented was up to 800%.

Moreover, the required interdisciplinary background for the modelling approach presented in Figure 2 presents an additional challenge. The majority of research community working in energy and buildings does not have an extensive background in climate modelling, nor the access to the computing power and resources necessary to develop and operate GCMs. Thus, in most cases, the only remaining option is to rely on the published reports from climate modelling centres and using available tools to transform the output data from climate models into weather data suitable for loading into building energy models. In order to cover the uncertainty aspects as much as possible, the authors can consider the outputs from multiple GCM models for multiple emission scenarios (as in the study of Wang et al. (2010)). However, assigning the probability of happening to each scenario would still be challenging.

Discussion

As discussed previously, evaluating climate change implications for architecture is a complex interdisciplinary approach which consists of coupled models with high uncertainty levels. However, all modelling approaches inevitably suffer from simplifying assumptions and associated uncertainties (Wiens, Stralberg, Jongsomjit, Howell, & Snyder, 2009). While modelling carries uncertainties, not using models to predict future conditions is a hardly acceptable option. The consequence would be the assumption that the future will be unchanged compared to the present (business-as-usual scenario), while the increasing amount of evidence suggests otherwise. Furthermore, idleness would result in long-lasting and irreversible consequences for the environment. Ultimatevelly, models are educated guesses about the developments in the future, and by stating the underlying assumptions, their potential impacts and investing continuous efforts in methodology improvements, the uncertainty range can be narrowed (Wiens et al., 2009). As indicated by Mahlman (1997), while sceptics may argue that attempts to model and describe the changes in dauntingly complex system such as climate are futile, climate models do a reasonably good job of describing and capturing the essential large-scale aspects. Finally, there is no viable alternative available.

While the forecasted rate of change in building energy demand comes with uncertainty, the trend is clear – heating demand in the future will decrease, while the cooling demand will increase. Such changes will have an impact on both building and energy systems design. For example, in cooling-dominant climates, adequate measures should be applied to mitigate the significant increase in the total hours of cooling demand and the building energy demand itself. Such measures should incorporate adequate renovation of the building envelope (in order to reduce the heat exchange between the building and environment) and behavioural measures (such as more energy efficient set point comfort temperatures and occupancy schedules). In regard to the urban energy systems, both district heating and cooling systems designed based on the current energy demand will become obsolete; due to the changes in building energy demand, district heating capacity will become oversized, while district cooling capacity will become undersized. In both cases, modification of the system will be necessary in order to secure optimal and efficient operation, which will increase the amount of capital investments required and prolong the investment return period, consequently impacting the feasibility of such urban energy systems. The uncertainty risk could potentially be managed by installing several smaller units instead of one high-capacity unit. In the case of energy demand increase, all units would be in operation, while in the case of decrease, excess capacity units could be removed from operation and dismantled. However, such solutions should also be evaluated through techno-economic analysis. To conclude, building renovation measures should be designed so that they mitigate any predicted decrease/increase in heating/cooling demand, while urban energy design systems should be designed to efficiently cover such demands.

The changes in building energy consumption patterns will also affect the overall sustainability of built environment. Building environmental performance is quantified by evaluating the environmental impacts of all major building lifecycle phases (construction, operation and demolition & recycling/landfilling), either through a Life Cycle Assessment (detailed bibliography review can be found in the studies of Anand & Amor, 2017;

Soust-Verdaguer, Llatas, & García-Martínez, 2017; Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017) or emergy assessment (Amponsah, Lacarrière, Jamali-Zghal, & Le Corre, 2012; Meillaud, Gay, & Brown, 2005; Pulselli et al., 2007; Reza, Sadiq, & Hewage, 2014). The majority of the studies indicated that out of these phases, operation phase has the highest contribution to the overall environmental impact over the lifetime, ranging from 50% to 95% (Bastos, Batterman, & Freire, 2014; Chang, Ries, & Wang, 2013; Andrić, Pina, Ferrão, Fournier, et al., 2017; Ortiz, Bonnet, Bruno, & Castells, 2009; van Ooteghem & Xu, 2012). In warm climates that will experience the highest increase in cooling (and thus energy demand and emissions), the impact from the operation phase could be further increased. Consequently, adequate mitigation through envelope renovation gains even higher importance. One might argue that the additional materials and resources during the renovation phase could increase the building environmental impact, however, the case studies proved that the emission savings enabled during the operation phase provide both environmental and economic benefits, as well as lower overall environmental impact (Andrić, Pina, Ferrão, Lacarriere, & Le Corre, 2017; Popescu, Bienert, Schützenhofer, & Boazu, 2012). Additionally, if the appropriate materials are used during the building envelope construction phase, negative effects of climate change could be reversed (Gámez-García et al., 2018). By choosing the adequate insulation materials, the impact of increased outdoor temperatures on cooling demand could be mitigated, and emissions from the building sector reduced.

Conclusion and outlook

Building sector is a major source of CO_2 emissions on a global level and significant efforts are being made to develop a more sustainable urban environment. However, potential changes in future building energy demand are frequently overlooked. Designing the future urban environment and energy systems based on current weather conditions is misleading: due to changing weather variables (direct impact of climate change) and the application of building renovation policies (indirect impact of climate change), current heat demand will decrease while the cooling demand will increase. Such potential changes in building energy consumption and heating/cooling ratios require careful consideration when developing building adaptation and renovation measures as well as urban energy systems. This study's primary purpose was to provide an up-to-date review of modeling approaches used for forecasting building energy demand, assessing impacts, and considering potential implications for building and urban energy systems design (sizing of the base load and peak load units, operational parameters etc.).

In order to develop future weather scenarios, the majority of studies morphed the typical meteorological year with output data from complex Global Circulation Models (GCMs), most commonly using CCWorldWeatherGen software. For the creation of building renovation scenarios, all studies reviewed relied on energy efficiency reports and/or codes from national or global energy agencies. Based on the review of building energy modeling approaches used for estimating the future energy demand, while their precision is satisfactory, there is an existing need for the development of a dynamic building energy demand model that is capable of dynamic heating/cooling demand calculations on a large scale (for the building stock on a neighbourhood, city, or possibly national level), but without significant calculation time nor computational power required. Such a model should consider all relevant building properties (geometry, thermal properties, occupancy profiles, etc.), both heating and cooling demand, weather and building renovation scenarios, and climate variations.

It is rather difficult to compare the climate change impact results of the studies reviewed, as different case studies considered different locations, time horizons, and climate change impacts while using weather and building data that were not always publicly available (especially in the case of large-scale studies). Thus, it is of outmost importance to clearly state the following information:

- Reference state conditions: weather parameters, building parameters (geometrical and thermal), and the ratio between the heating and cooling demand for the reference conditions;
- Studied time horizon for the scenarios;
- Future weather conditions, building parameters, and the ratio between heating/cooling demand after the application of scenarios;
- Whether the results obtained should be interpreted as energy demand or energy consumption, or provide a conversion factor used;

However, some general observations can be made based on the case studies that had one scenario year in common and compared the energy consumption for reference conditions (pre-2020). These results suggest that modifications in building envelope thermal performance will have a significantly higher impact on building heating demand in the future, while changing weather conditions will have a more significant impact on cooling demand. On average, heating demand in 2050 will decrease by 7–52%, while cooling demand will increase by up to 1050% compared to reference levels (with variations depending on the properties of the studied buildings and climate conditions). The main uncertainty that causes such a huge range in predictions comes from the global emission scenarios and climate models (GCMs). Additionally, the credibility of GCM outputs is limited when the focus is on smaller scales: an increase in model resolution generates more spatially detailed, but not necessarily more accurate, weather predictions. Another uncertainty comes from building renovation scenarios: while the proposed renovation policies suggest renovation rates in order to meet the sustainability goals set, in reality, current renovation rates are significantly lower. While modeling approach carries inevitable uncertainties, currently there are no other available options, and assuming business-as-usual scenario for the future would have irreversible consequences. Moreover, for policy makers, it should be acceptable to provide tendency in lieu of precise values as a result, since the purpose of modelling is to guide the policy rather than dictate it, due to the fact that additional factors have to be taken into account for policy making (sociopolitical, economic, etc.). Thus, modelling studies should consider multiple scenarios and provide a range of results, but should also include the efforts to assign probabilities to scenarios and consequently the results. Moreover, to reduce the uncertainties from coupling different models, climate modelling, building modelling and environmental impact assessment research groups should work in close collaboration.

It is the opinion of this review's authors that future studies should consider renovation measures which are currently not incorporated into the national renovation plans and policies. For example, the integration of green roofs and green walls should be considered due to the fact that multiple simulation and experimental studies from the bibliography concluded that these technologies have a positive impact on building energy demand, due to their shading, evapotranspirative, and insulation effects (Cameron, Taylor, & Emmett, 2014; Chen, Li, & Liu, 2013; Hoelscher, Nehls, Jänicke, & Wessolek, 2016; Jim & He, 2011; Koyama, Yoshinaga, Hayashi, Maeda, & Yamauchi, 2013; Manso & Castro-Gomes, 2015; Mazzali, Peron, Romagnoni, Pulselli, & Bastianoni, 2013; Olivieri, Olivieri, & Neila, 2014; Penaranda Moren & Korjenic, 2017; Pérez, Rincón, Vila, González, & Cabeza, 2011; Safikhani & Baharvand, 2017; Wong et al., 2010; Yin et al., 2017), as well as their potential environmental (Manso & Castro-Gomes, 2015; Pan & Chu, 2016; Pulselli, Pulselli, Mazzali, Peron, & Bastianoni, 2014) and economic (Perini & Rosasco, 2016). Such benefits could be crucial, especially in hot climates that are most sensitive to direct climate change impact. Green walls should also be considered as a part of urban regeneration process (the process where additional green surfaces are introduced into the urban environment in order to mitigate the heat island effect (which is a consequence of urbanization), reduce the energy consumption and improve the quality of life for residents). Moreover, urban regeneration in some cases incorporates the modification of the existing buildings use, such as transformation of abandoned industrial areas into commercial areas or social housing. Such buildings have even lower thermal efficiency than similarly aged residential building stock, and it relevant to consider their envelope renovation during the regeneration process.

Based on the findings from the scientific studies and intergovernmental studies reviewed, the probability of the energy demand trend suggested is extremely likely due to the fact that heat waves will occur more often and have a longer duration. The effect will be amplified even more in regions with severe climates. By adequately modelling building performance under future weather conditions, and defining adequate renovation measures, urban energy system design and associated policies, significant carbon savings can be achieved. Reducing building energy consumption, especially in the countries whose national energy systems are heavily based on fossil fuel combustion and already have a significant environmental impact (such as Gulf Cooperation Council countries) would have additional cross-sectorial benefits. Since the fossil fuel exports are pillars of economy for such countries, reduction of resource self-consumption would increase the quantities available for export and international trade. Thus, building renovations would result in both environmental and economic benefits and improved overall national sustainability and resilience. Considering the already existing discrepancy between the number of case studies available for developed (such as E.U.) and rapidly developing (such as Gulf Cooperation Council) countries, further research efforts should be invested in quantifying the climate change impacts on the built environment and associated challenges in developing countries, especially the ones with a rapid built environment growth rate (such as Qatar and United Arab Emirates). Additional aspects that should be considered within scenarios of such studies are population increase, integration of large-scale renewable energy sources, and the development of new types of energy systems.

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