Predicting the Energy Performance of Buildings Under Present and Future Climate Scenarios– Lessons Learnt

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***Abstract*— Predicting the energy performance of buildings is important to optimize the energy consumption. Building Energy Performance Simulation (BEPS) is a key tool that is used to predict the environmental performance of buildings. Much work has been done that conforms a gap between predicted and measured energy consumed in buildings due to a range of influencing factors. Understanding the causes of performance gap can help in reducing it between design targets and actual performance. On the other hand, there is a convincing evidence that climate is changing and that we will be facing different climatic scenarios in the future. Buildings should be designed to be able of dealing with future climatic changes using mitigation and adaptation measures. Building Energy Performance Simulation (BEPS) can be used to estimate the energy performance of buildings and their indoor environments based on future climatic scenarios and to assess the different design options. This paper explores the main aspects that need consideration when predicting the energy performance of buildings under future climatic conditions. The research conducts a critical literature review engaging with previous knowledge in the field. It also sheds light on the way of producing future weather files.**

Keywords: Climate change; Building Energy Performance Simulation (BEPS), performance gap, future weather files, mitigation and adaptation

I. INTRODUCTION

The scientific community warns that if the global average temperature will rise more than 2◦C by 2050 that will have catastrophic environmental consequences. To prevent that to happen it is crucial to reduce emissions to at least 50% of the 1990 emissions levels by 2050, this is what is known as“2◦C” challenge [1]. In addition to the mitigation potential in such policies, it is important to consider adaptation measurements [2]. The majority of the building stock in the United Kingdom (UK) and the European Union (EU), falls towards the bottom of the energy efficiency rating scale on the EU Energy Performance Certificate [3]. Several countries in the world such as the UK and the European Union countries e.g. Sweden and Italy, found that buildings are key area for meeting Kyoto obligations and they are creating policies for reducing buildings' energy consumption [4], [5], [6]. In order to meet this goal; governments should not only focus on designing the new buildings to high standards, but also to consider retrofitting of the existing building stock to be more energy efficient and more adaptive to future climatic conditions. Understanding the pattern of energy usage is important to optimize the energy consumption in the buildings for professionals and policy makers. This is also important in order to alleviate environmental stresses like the depletion of conventional energy sources, increasing ecological footprint, growing CO^2 emission rates …etc. [7], [8]. There are several ways of estimating the energy demand in building such as *Heating and Cooling Degree Days (HDD) (CDD)* [9] and *the heating and cooling demand* [10]. However, this paper will discuss Building Energy Performance Simulation (BEPS). The paper also investigates the factors affecting energy consumption in buildings; the energy performance gap and the reasons behind it, and initiatives to overcome the performance gap. The paper then addresses predicting future climatic conditions and creating future weather files for estimating energy demand followed by a discussion of Future emissions scenarios. Then it discusses the need for creating future weather files for predicting the Performance and estimating the energy demand of buildings

II. THE FACTORS AFFECTING ENERGY CONSUMPTION IN BUILDINGS

The determinants that influence the energy consumption in buildings has been studied extensively [11], [12], [13], [14], [15]. The increase of population, the higher standards of living (like the higher levels of thermal comfort and the increase of ownership of domestic appliances), larger homes and the changes in the digital technology has all contributed to the accelerated energy consumption [16]. The International Energy

Agency (IEA) launched the Energy in Buildings and Communities Program (IEA-EBC) that aims to provide high quality scientific reports to help decision makers in improving energy efficiency of buildings [17]. As part of this program, the IEA Annex 53 project defined the factors that affect energy consumption in buildings which are: Climate, building envelope, building systems, operations & maintenance, occupant behaviour, indoor environmental conditions [18]. In addition dwelling characteristics affects the energy consumption. Mileham and Brandt have found that the best predictor of money spent on energy is the size of a dwelling [19]. Housing typology and building shape is also an important factor determining the energy consumption [20].

A study conducted in Oxford Brookes University of the energy consumption corresponding to the different orientations, emerged that a well-orientated building can up to 17 056 kWh of electricity and 27 988 MJ of gas throughout a 30 year period. [21]. Dombaycı et al.,(2006) proposed that the building envelope characteristics plays an important role in the energy consumption [22]. They suggested that using appropriate thermal insulation, can play a significant role in energy –saving in the building. It is also believed that an increase of vintage of a dwelling relates to a noticeably increased amount of energy consumed for heating or cooling of the indoor environment [23]. This was also proved by Wiesmann et al.; (2011) found that newer homes in Portugal consumed [24].

Besides, energy policies affect the energy consumption, hence, it is important to design a proper policy scheme to regulate energy consumption including the domestic intake [26]. However, their effectiveness has been demonstrated to be dependent upon enforcement [27].

The energy consumption in the residential sector is also affected by the household socio-economic characteristics like number of the family members, the family structure and income [28], [29], [30], [31]. On the other hand, the affordability and accessibility of fuel impacts the amount and type of energy used [32]. See graph 1, that illustrates the main factors that affect the energy consumption in buildings.

III. BUILDING ENERGY PERFORMANCE SIMULATION (BEPS):

Building energy performance simulation is widely used to predict actual performance of buildings [33], and has several applications in the world today [34],[35]. It involves constructing a model of the design for which a range of simulations may be performed using different configurations and assumptions. The performance for different scenarios may be compared against the baseline model and/or against each other's. [36]. This process is also called optimization, through which the best set of configurations will be identified in order to optimize the performance of design [37]. Furthermore, one of the main aspects towards developing a successful building energy simulation model is having a set of appropriate typical weather files to present to local climate [38]. In order to validate the baseline model is essential to introduce a climatic data compatible with the monitored values [39].

During the past five decades, a wide variety of building energy simulation programs have been developed and used such as DOE-2, EnergyPlus, eQuest, ESP-r, IES-VE, TRNSYS …etc [40], [41]. The models used in building energy performance simulation (BEPS) can be roughly subdivided into two main categories: first, the steady-state models [42], [43], [44], and the second the dynamic models [45], [43]. The table 1 below indicates the main differences between the two models.

Building energy performance simulation (BEPS) tools can be used in several stages of the life span of the building. Early design stage require simple simulation program to determine the orientation of the building, massing or other early design issues [40]. In later stages simulation programs can be used to estimate the heating, cooling and lighting demand, the contribution of particular technologies like advanced glazing

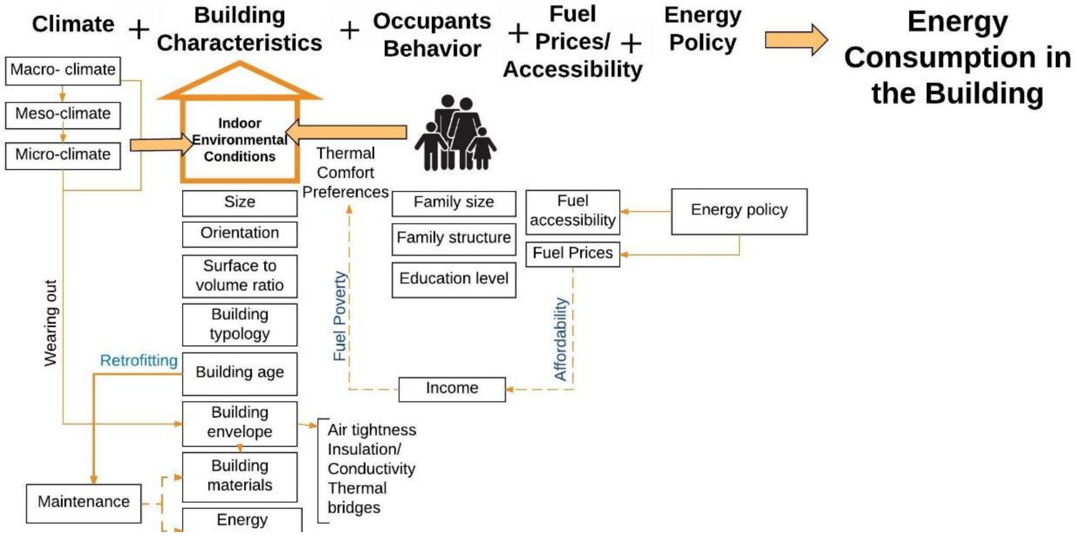

Figure1, The factors affecting the energy consumption in the building/ dwelling

Table 1, Comparison between the steady state and the dynamic models in energy building simulation

	Steady state model	**Dynamic model**	(Source)
Time scale of prediction	Days/ months/ years	Hours	[46][47]
Complexity of the input data	Simple input data	Detailed data of materials and building characteristics	[36]
Fixed/ Variable inputs	Fixed inputs (like max and min temperatures, air exchange rate), do not consider the transient effect of variables, regresses monthly actual energy consumption data against outdoor climate parameters	Variable/ Changing inputs , modelling complex systems that are dependent on more than one independent parameter, can track peak loads and are useful to capture thermal effects like thermostat setback strategies	[47]
Dynamic characteristics of the building	does not consider the time related characteristics of the building	considers the dynamic characteristics of the building like thermal inertia	[48]
Accuracy	Not very accurate	Accurate with detailed input data and long simulation time	[39]

or smart controls and the potential and feasibility of applying renewable energy systems [49]. For existing buildings, energy simulation has a number of applications like retrofit analysis, measurement and verification, calculating savings from energy conservation measures and estimating losses due to systems' deficiencies [50].

IV. THE ENERGY PERFORMANCE GAP:

There are great benefits of building energy performance simulation (BEPS) in terms of affordability, flexibility and time saving. On the other hand, the complex relations between the factors that affect the energy consumption, makes it hard to predict the energy consumption in a building in a precise way. Recently, there is a growing concern within the building industry about the difference between the calculated (predicted) and measured (actual) energy use-when buildings are in real life condition of execution and operation- which is referred to as "the performance gap" [51], [52], [53], [54], [55], [56], [57], [58], [59], [60]. The term was first brought out in 1994 and studies continued to address the issue afterwards [61].

There is a great variation in the size of the gap [16]. A study took place on 25 recently built dwellings in the UK, indicated that the "performance gap" in the majority of the dwellings was considerable -between 6 and 140% and on an average of 50%- [62]. In non-domestic buildings, the reports showed that the gap can reach 250% of the predicted energy use [55]. The gap also was found in retrofitted buildings [3], [60]. A project that took place in Switzerland, assessed 10 multifamily post war buildings after retrofitting showed that the actual heating energy savings was 29-65% less than what calculated [54]. Similar to that, a study addressed the performance gap in heating demand of 7 dwellings in Germany, found that the gap of the entire field test varied from 117% in 2011, 107% in 2012, 41% in 2013 and 60% in 2014 [63]. The following section will explore the main reasons behind the performance gap in several stages during the life of the building.

V. THE REASONS BEHIND THE PERFORMANCE GAP:

The causes behind not meeting the predicted energy during real life performance can go back to different stages of the building life starting from the concept and planning, design phase, procurement, construction, testing and occupation not forgetting the building materials [16]. A combination of reasons in the previous stages can be found in many buildings [51].

During concept formulation and planning phase, the aim of constructing low energy building might not be emphasized to the design team, especially when several bodies are involved in concept formulation [64] .The traditional linear design process starting from the architect, followed by the engineer (Civil, mechanical and electrical), and the contractor and finally the occupants, neglects the interdependent relation between the different roles in this process, especially in terms of energy consumption and efficiency measurements [65] . For example, the designer makes design decisions according to the skills he thinks the construction industry has [16]. Furthermore, changing requirements through the design phase might not be reassessed for energy performance [16].

Designers sometimes are forced to make significant assumption due to insufficient data during the design and energy simulation phase [66], [41]. Some of these shortcomings can be overcame using Building Information Modelling (BIM), however, this software is still not very widely spread [67].

Energy performance depends on the physical qualities of the building materials The physical characteristics of the materials

is usually measured in laboratory conditions, however, the onsite performance of the materials can be different [16]. Simulation usually does not consider the onsite performance of the materials [68]. In addition, complex and specific procurement processes can cause discrepancy between actual and theoretical performance [69]. For example, some building materials can be substituted with others with lower specifications, and some jobs related to energy efficiency is not clearly defined by whom should be executed [16].
Poor construction practices are among the factors for the mismatch between the predicted and measured energy [70]. The quality of building is sometimes not in accordance with the specification, with insufficient attention to both insulation and airtightness with potential risks for the creation of thermal bridges [71]. Such complications where actual construction does not meet specification is usually not easy to define, as buildings components consist of various layers [72]. Quality control in addition to tests such as air quality, air tightness, U value measurements, and thermal imaging are important for improving the construction practices , reducing the performance gap and can present a valuable feedback for the designers to improve the energy efficiency in future projects. [55]

Occupants' behaviour effect on the energy performance of buildings has been addressed extensively in the literature [73], [74], [75] .The behaviour of the occupants has substantial impacts on the energy performance of buildings, however its precise impact is not very certain [74]. However, it is hard to be comprehend due to its chaotic, diverse, complex, and interdisciplinary nature. Hence, in most of the times it is oversimplified in the building life cycle [76]. There are several issues related to occupant's behaviour that should be taken into account when in retrofitted buildings can be due to three reasons, rebound effect, pre-bound effect and quality of the retrofit [77]. The "rebound effect" is considering the performance gap. Among these are the pattern of occupancy and the operation of control systems [16]. Adding to this, falling to predict the energy savings due to energy efficiency measurements a term that describes a phenomenon of: increasing the energy efficiency leads to more energy consumption [3]. The pre-bound happens when energy consumption before retrofitting is over estimated [78].

Understanding the way in which the occupants interact with the building can help the designer to avoid making critical assumptions. Assumptions during the design phase can cause serious mismatch between predict and actual performance. For example assuming certain internal temperature that differs from occupants preferences can cause "comfort gap" [63]. There are several models of anticipating the way that occupants interact with the building. The post occupancy evaluation POE that aims to feedback data into the design process is the most common [55]. Niu et al., 2015 believe that such models consider the interaction between the occupants and the buildings as a basic behaviour neglecting of the influence of building design [74]. They also criticise the previous models as they lack some important considerations. For example, the data regarding the way of occupants interact with the building and its systems are not given upon the exact building that is to be built. Alternatively, a virtual reality integrated design approach was introduced in their study to improve occupancy information integrity in order to close the building energy performance gap [74].

VI. INITIATIVES TO OVERCOME THE PERFORMANCE GAP

Energy performance gap is a critical obstacle in front of achieving energy efficient buildings. Several initiatives had been developed trying to overcome it. As we have discuss above, the fragmentation of the building process activities and the segmentation of responsibilities are main barriers for producing energy efficient buildings [65]. Building information modelling (BIM) is a valuable tool to increase the synergies and rise the communication and increase the data flow between the professionals who are involved in the building process [67] . Learning from the previous projects is crucial to assure developing more energy efficient buildings. Post occupancy evaluation (POE) and benchmarking gives a feedback informing the professionals of any problems and comparing the actual energy consumption with the benchmarks [16]. Benchmarks helps to quantify of the size of the performance gap in the building [16]. In addition, commissioning as a cost effective systematic quality assurance process; can be a great opportunity to fall down the performance gap by assuring proper performance of the systems [79].

In the UK the Building Services Research and Information Association (BSRIA) is a testing, instrumentation, research and consultancy organization. In cooperation with the UBT (Usable Buildings Trust), it has developed the Soft Landing Initiative in 2009 that aims to develop communication throughout the different phases. It introduces steps to be involved which are Inception and briefing, Design development and review, pre-handover, initial aftercare and extended after care and POE [16].Full description of the Soft Landing Initiative can be found on the BSRIA website.
Building Energy performance Simulation (BEPS) is an important tool to design energy efficient and low carbon buildings, however, literature demonstrates a significant gap between the predict and the actual energy performance of the buildings. The reasons behind the gap spreads over the whole life cycle of the building. Among the lessons to be learnt, communication between the different professionals is important to meet the calculated energy performance. In addition, great emphasis should be given to the commissioning and occupation stage for assessing the buildings performance. It is important for the professionals to understand how the occupants interact with the building to assure the efficiency of the building and to bridge the performance gap. Current construction projects usually exclude users from fully participating during the design, especially for residential projects in which residents get involved only in sales [80].

VII. PREDICTING FUTURE CLIMATIC CONDITIONS AND CREATING FUTURE WEATHER FILES FOR ESTIMATING ENERGY DEMAND:

In order to use BEPS for predicting the energy demand, weather files are needed for the location of the assessed building [81] .Weather files are not the average of weather parameters over a certain period, but rather a samples of real weather files taken from this period which are similar to the average of the weather parameters [82] .The most popular weather files are the International Weather Year for Energy Calculation (IWYEC) developed and used by ASHRAE, the Typical Meteorological Year (TMY) which is mostly used in the USA and the Example Weather Year (EWY) developed by Chartered Institution of Building Services Engineers (CIBSE) that is used in UK [82]. There is a certain criteria for selecting the representative years for each file. For example in the (IWYEC) and (TMY) files are created using a statistical method to choose the most representative months from the 15 or 30 years of data, then the months are combined to shape a composite year of weather data [83]. Creating weather files for the future is more challenging. In order to clarify the methods of creating future climate weather files it is important to define the future emission scenarios.

VIII. FUTURE EMISSIONS SCENARIOS

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body that was established in 1988 under the umbrella of the United Nations [84]. Its main goal is to provide stockholders with regular assessment reports [84]. The reports cover the scientific basis of the climate change, its effects and future risks in addition to the choices for adaptation and mitigation [84]. Since establishment, the IPCC has published five main reports (FAR), (SAR), (TAR), (AR4) and (AR5). In 1990, the first assessment report (FAR) expected that rate of increase of global mean temperature during the 21 century of about 0.3°C per decade [84]. The “IS92” were the emission scenarios developed for the 1992 Supplementary Report to the IPCC Assessment [85]. The future greenhouse emissions were predicted based on population growth, economic growth, land use, technological changes, energy availability and fuel mix [85]. The second assessment report (SAR) was published in 1996 relied upon IS92 and pointed out to the increase of the GHGs [86] .In 2000 the IPCC published Special Reports on Emissions Scenarios (SRES) to develop some of the aspects in IS92 scenarios[87]. There are 40 SRES scenarios which depends on human future activities [87]. These scenarios are classified into families. IPCC used A1FI, A1B, A1T, A2, B1, and B2 families in the 3rd assessment report (TAR) in 2001, and in the 4th Assessment Report (AR4) in 2007 [87](see fig 2).

The overall mean warming is relatively alike through these emissions scenarios during the next few decades but fluctuates afterwards [88].

The fifth assessment report (AR5) in 2014 adopted four greenhouse gas concentration (not emissions) tracks which are the Representative Concentration Pathways (RCPs) for future climate anticipation [89]. Four possible paths are included which are RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5 [89]. The RCPs define four sets of future climate pathways in terms of GHG emissions: very low (RCP2.6), low (RCP4.5), medium (RCP6.0) and high (RCP8.5) [90]. (see figure3)

Regional climate models can be created based on the IPCC’s global climate scenarios to be used on local scales using downscaling techniques [91]. Regional models showed a significant improvement in modelling spatial weather patterns.

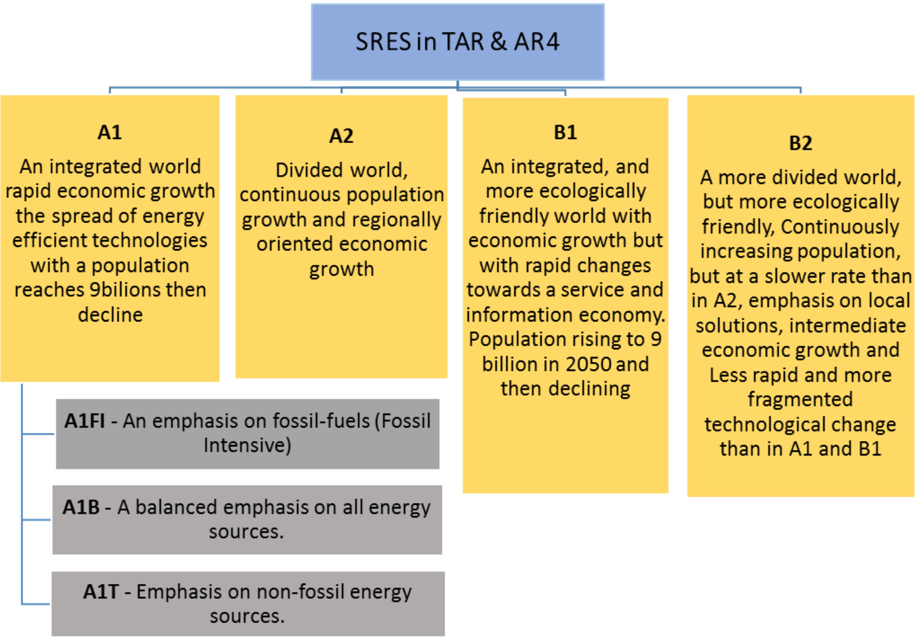

Figure2, SRES scenarios used in TAR and AR4, based on [88]

For example in the UK, the levels of climatic change presented in UKCIP02 model was developed by the Met Office Hadley Centre and the UK Climate Impacts Program in 2002 [92]. The UKCIP02 scenarios consist of a set of climate change data for the years 2020s, 2050s and 2080s for four different global carbon emission scenarios: low, medium–low, medium–high and high emissions that are connected to the four SRES emission scenarios [93]. Later on the UKCIP02 were superseded by UKCP09 that provided uncertainty levels in future scenarios [94]. In 2016 the UKCP18 project was announced and will build upon the current set of projections (UKCP09) [95].

IX. Creating Future Weather files for Predicting the Performance and Estimating the Energy Demand of Buildings

There are two main methods to develop future weather files to be used in building simulation. The first is the mathematical transformation of historical weather data (morphing) [96] and the second is using a weather generator [82] .The main concept of the morphing procedure is to morph the present-day observed weather files, the baseline climate, to produce future climate weather files using predictions from either a global or a regional climate model [96] .The changes produce monthly-mean values of the weather variables [96]. This method has been used to examine the future thermal comfort of a faculty building in the UK [81] ,and to assess the future climate impact on the heating and cooling energy requirements in residential buildings [97] .A full description of the morphing method can be found in [96]

Weather generators are tools that uses numerical analysis for generating time-series of climatic variables which are statistically similar to the real climate [98] .They were first developed for the daily timescale daily series of precipitation amounts, mean temperature and solar radiation to drive a crop-climate model[98]. Several weather generators has been developed since then as Met&Roll and EARWIG [99], [90]. In a study that aimed to evaluate the impact of passive design strategies on the heating and cooling energy demand in houses in Brazil, Climate Change World Weather File Generator (CCWorldWeatherGen) was used to predict future typical meteorological years, such as 2020, 2050 and 2080. [100] A detailed technical description of the weather generators is presented in [90].

It is worth to mention that the impact of global climate change is asymmetric [101], and the main idea of creating future climatic weather data sets is to downscale the future global climatic models in order to be used on local levels. However, the previously mentioned methods are both highly scenario-dependent [15]. Furthermore, climate change might be parallel with unexpected climatic conditions [102]. These facts makes developing accurate future weather files a more challenging issue.

X. Discussion

The paper explores the main aspects that influence the energy consumption in buildings, and the use of simulation as a tool for predicting the energy performance. It also sheds light on the performance gap, its causes and how to overcome this problem. The paper then illustrates how future climate weather files are produced to be used in predicting future performance of buildings.

There are a number of socio physical factors that determines

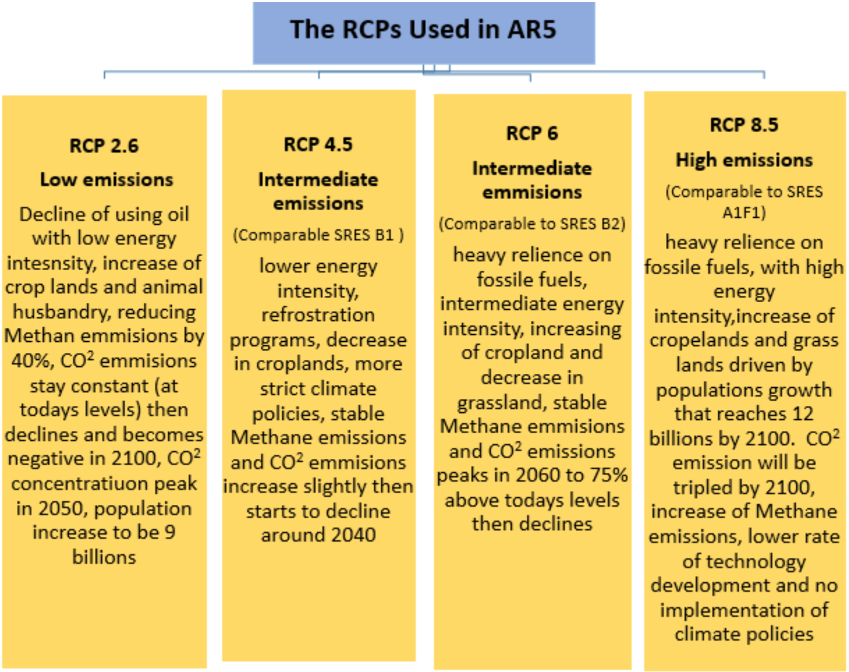

Figure3, RCPs used in AR5, based on [90].

the energy consumption of buildings. The energy policy also plays an important role. Predicting the energy consumption and the performance of buildings is essential for the occupants and even for policymakers. However, there is a considerable mismatch between the predicted and actual energy performance of buildings. Through literature review we can consider a number of determinants behind the mismatch. Some of these factors go back to the design phase which can include wrong assumptions, simplification or deficiencies of the simulation programs. Other factors relate to the construction phase were the building does not comply with the specifications. In addition, there are factors that is related to the operational phase including systems inefficiency and human behaviour.

Unlike most of the products, buildings are usually built to serve for decades. Decisions that we take as designers now can have a long lasting effects. Climate is a main factor when defining the thermal performance, energy savings and the indoor environment quality for any building. Climate change has been demonstrated and recognized as one the most challenging environmental issues that should be managed on different scales through mitigation and adaptation [103]. In the UK for example, it is predicted that the heating energy demand will decrease and future cooling demand will increase leading to an uptake of cooling technologies [104]. Hence, it is vital to take into consideration future climatic conditions while modelling the energy performance of the buildings.

Several studies have aimed to project the thermal performance of buildings in the shadow of climatic design [105], [106], [107]. To be able to predict the future heating, cooling demand, energy savings…etc, it is important to obtain future weather files for the area of the assessed building [108].

The fifth assessment report (AR5) in 2014 adopted four greenhouse gas concentration tracks: the (RCPs) for future climate anticipation. Predicting the actual energy performance is linked to which scenario will take place in the future. In addition, the chance to experience unexpected climatic conditions exists [102], making the prediction of energy consumption challenging. Figure 4 explains how the performance gap can increase when predicting future energy performance of the building. In order to increase the accuracy of the future EBPS it is essential to reduce the performance gap we face and already know in the present. This is possible by adopting a socio-technical approach when predicting the future energy performance of the building [100]. It is important to mention that predicting future performance will be also affected by probable changes on the social characteristics of the occupants and physical deterioration of the building as well.

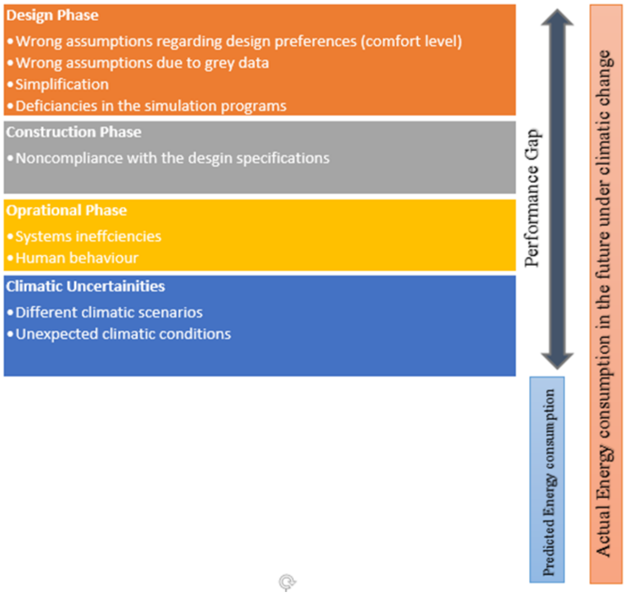

Figure 4. The main factors that contribute to performance gap under future climatic conditions

XI. CONCLUSION

There are several factors that determine the energy performance of the buildings. These factors are not only physical, but there are also social factors which determines the way that the occupants interact with the building. Buildings have a great potential for energy savings and reducing the CO^2 emissions that contribute on the climate change. On the other hand, the climate change carries a number of confrontations such as overheating that leads to increasing on the energy demand for cooling. This circle should be broken. Predicting the accurate buildings performance energy and the consumption of buildings is important to alleviate indoor environment problems caused by climate change. A socio technical approach should be adapted when carrying out energy simulation. Furthermore, a more synergetic process should be emphasized, considering the occupants involvement from the early stages in the design process. Developing accurate weather files to be used in the prediction procedure is a key factor for the success if this process.

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