Current and future demand-side management potential related to the thermal mass of residential buildings in Europe

Background and methodological approach

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Manuel de-Borja-Torrejón
Technical University of Munich
Universidad de Sevilla

Ángel-Luis León-Rodríguez
Universidad de Sevilla

Thomas Auer
Technical University of Munich

Preface

The present work has been elaborated in the framework of the ongoing doctoral research project entitled “Comparative study of the present and future demand side management potential of buildings in northern and southern Europe, with focus on the heat storage capacity of their thermal mass” by Manuel de-Borja-Torrejón.

The mentioned doctoral research project is been jointly supervised by Dr. Ángel-Luis León-Rodríguez at Universidad de Sevilla (US) and by Prof. Dipl.-Ing. Thomas Auer at Technical University of Munich (TUM)

The presented paper was submitted for blind peer review and was selected following a strict method of content filtering in terms of its veracity, scientific definition and quality. The scientific committee who carried out the selection of the work is of international character and of recognised prestige.

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CURRENT AND FUTURE DEMAND-SIDE MANAGEMENT POTENTIAL RELATED TO THE THERMAL MASS OF RESIDENTIAL BUILDINGS IN EUROPE BACKGROUND AND METHODOLOGICAL APPROACH

de-Borja-Torrejón, Manuel [(1)]; León-Rodríguez, Ángel-Luis [(2)]; Auer, Thomas [(3)]

(1) Technical University of Munich, Universidad de Sevilla, manuel.de-borja-torrejon@tum.de
(2) Universidad de Sevilla, leonr@us.es
(3) Technical University of Munich, thomas.auer@tum.de

Abstract: The aim of this article is to present a summary of the state of the art and the methodological approach, included in the research proposal of an ongoing doctoral thesis investigating demand-side management in buildings. This resource can help balance electricity consumption and its variable production from renewable sources. The use of demand-side management could contribute favourably to the transition towards an energy model based on renewable energies, and the achievement of climate objectives set to reduce greenhouse gas emissions. The thesis focuses on the demand-side management potential associated with the use of the building mass, whose thermal properties enable the adaptation of the operation of heating and cooling systems, while maintaining thermal comfort. The impact of climate change and the improvement of the energy efficiency of the building stock on the potential of demand-side management are addressed. To this end, a comparative analysis of the current and future potentials of residential buildings in Europe, located in continental and Mediterranean climatic zones, is planned by applying a combination of experimental and predictive methods. The considered hypothesis poses that, due to global warming, the demand-side management potential associated with the use of the building mass could increase in the continental climatic zone and decrease in the Mediterranean zone. A drastic reduction of these potentials owing to an overall implementation of highly energy-efficient standards in buildings is additionally assumed.

Keywords: Climate change, Energy system, Energy efficiency, Demand-side management, Thermal mass.

1. Introduction

At the 2015 Climate Change Conference held in Paris, the participating countries agreed that by the second half of the XXI century, global greenhouse gas (GHG) emissions should be limited to levels which can be naturally dissipated (United Nations 2015). Therefore, Europe expects to achieve an 80-95% reduction in GHG emissions by 2050, with reference to levels emitted in 1990. To fulfil this objective, the European Commission (EC) has designed a roadmap with implications for the main sectors, in order to undertake the transition towards a more efficient energy model mainly based on renewable energies (European Commission 2016).

According to these guidelines, the cut in emissions within the building sector should reach 90%. The implementation of better standards of energy efficiency in new buildings offers a limited contribution, given the low proportion of this type of constructions. Moreover, the retrofitting of the rest of the building stock is not reaching the necessary rate (European Commission 2017a).

On the other hand, according to the EC, the electricity sector has the highest potential for reducing GHG emissions in Europe. The extensive integration of renewable energies for electricity production is a key priority in this area, which will ideally be implemented along with a gradual dismantling of conventional power plants, based on the consumption of fossil fuels. However, this presents a challenge for the power system, in terms of ensuring both the security and affordability of the electricity supply in the future. The continuity of electricity provision requires a balance between production and demand. Currently, this balance is mainly based on the adaptation of the production to the existing demand. In order to achieve this, the possibility of controlling electricity generation by regulating the operation of conventional power plants is an essential aspect. However, the production of renewable energy, such as wind and photovoltaic solar energy, is characteristically volatile due to its dependence on natural resources. The configuration of an electrical system principally based on this type of energy requires the application of measures which contribute in an economically and technically feasible way

to the balancing of fluctuating electrical production and electricity demand. Boosting *Demand-Side Management* (DSM) according to energy availability represents a possible alternative to address this situation.
These circumstances call for the consideration of a synergy between the building sector and the power sector, through the active participation of buildings as flexible consumers in the electricity system. This synergy consists of making use of the DSM potential associated with the thermal mass of the building stock. Such a potential derives from the use of the thermal properties of the building mass in order to adapt the operation and, consequently, the energy consumption of the heating and cooling systems, while also maintaining thermal comfort. This combined performance of both sectors has several purposes. On the one hand, it is intended to contribute toward regulating the electrical system and ensuring the electricity supply, favouring the incorporation of renewable energies and the reduction of emissions in the power sector. On the other hand, the aim is to achieve additional emission cuts in the building sector by means of a greater coverage of the energy needs of buildings with electricity generated from renewable sources by the power sector.
The doctoral research on which this publication is based, aims to broaden scientific knowledge with regard to the dimension and availability of the aforementioned DSM potential. The main objective of the study, recently initiated and jointly supervised by the Technical University of Munich (TUM) and *Universidad de Sevilla* (US), is the analysis of the impact of climate change and the extended implementation of highly energy-efficient building standards on this resource. To this end, the study of the current and future DSM potential related to the thermal mass of residential buildings in Europe, comparing the situation in continental and Mediterranean climatic zones, is addressed. The aim of the present article is to present a summary of the analysis of the state of the art and the methodological approach, which were elaborated to define the research proposal.

2. Methods

To undertake the study of the state of the art, a literature search was carried out within the databases of *Web of Science*, *Scopus*, *Google Scholar* and *mediaTUM*. The key words *demand-side management*, *load management*, *thermal mass*, *energy system*, *electrical system*, *climate change* and *global warming* were used. The search was conducted in Spanish, English and German, and it was limited to studies published from 2007 onwards. From the results obtained, a first selection of references was made, based on their affinity with the subject of this doctoral research, namely the DSM of buildings associated with the thermal mass. To this effect, the objectives and results of the different studies were principally analysed. A more detailed review of the selection was then carried out. For this purpose, details on study cases, procedures, methods and tools in the publications were also analysed. Based on this analysis, the selected sources were classified into three groups. The first group corresponds to studies which point out the relevance of the role that the DSM could play in the successful integration of renewable energies in the electrical system. The second group contains references which indicate the possible use of the thermal mass of buildings in making their demand more flexible and promoting the aforementioned integration. The third group intends to cover examples of different methods of estimating the DSM potential of buildings. As a consequence of the classification structure proposed, some works were allocated to more than one group. The summary of the state of the art presented in this article includes a total of 15 scientific references, covering different types of publications.
The methodological approach of the research proposal was elaborated based on the conclusions drawn from the analysis of the state of the art. For its definition, a needs assessment for the determination of the study objectives, and an analysis of the available resources were carried out. A distinction was made between *documentary resources* (access to bibliography and data), *computing resources* (calculation, simulation and prediction software), *experimental sources* (testing facilities and measurement equipment), *personal resources* (advice and supervision), and *economic resources* (financing). Additionally, an initial specification of the case study of the research project was carried out. Finally, the procedures, tools and methods to be applied were established. To this end, the information analysed in the study of the state of the art was taken into account, with special attention being paid to the methods used in the selected works.

3. Summary of the state of the art

Amongst the literature linked to the present research topic, various terms related to DSM might be encountered. A reflection of this is provided by Benetti et al. (2016), who in their article differentiate between *Demand-Side Management*, *Demand Response* and *Electric Load Management*. On the other hand, Hausladen et al. (2014) distinguish between the German terms *Energiemanagement* (*Energy Management*) and *Lastmanagement* (*Load Management*). Jungwirth (2014) also refers to this terminological variety. While the description of these diverse terms occasionally include slightly differentiating nuances which refer to particular conceptual aspects of these, Jungwirth comments that, generally, the use of the different terms is not clearly defined. As a result, they are used interchangeably in a large portion of the available literature. Thus, Jungwirth considers *Demand-Side Management* and *Lastmanagement* as synonyms and defines them as follows:

Demand Side Management/Lastmanagement ist eine zeitliche Verschiebung oder Anpassung der Verbraucherlast aufgrund wirtschaftlicher Anreize. (Demand-Side Management / Load management is a temporary shift or adaptation of the consumer load owing to economic incentives).

Based on this interpretation, in the proposed doctoral research project DSM has been defined in a broader and simplified way, as *the intentional adaptation of the electricity consumption*. In this way, it is implied that DSM might be implemented owing to further factors such as the availability of low-carbon energy. On the other hand, the concept of the DSM potential of buildings associated with the use of their thermal mass consists of *the ability to adapt the electricity demand for heating and cooling while also maintaining thermal comfort, through the use of the thermal properties of the building mass.*

3.1. *Electrical system and integration of renewable energies through DSM*

In this field the following studies based on the case of Germany can be highlighted. The research work by Klobasa (2007) shows that, in view of an increasing presence of renewable energies in the future, the regulation of the electrical system by incorporating DSM could be a cost-effective alternative to exclusively managing power generation in order to ensure electricity supply. For her study, the author developed a simulation model, in which different degrees of integration of wind power in Germany's supply system were analysed. In the calculations, Klobasa implemented her own estimations of the amount of adaptable consumption of electricity within the industrial, tertiary and residential sectors. These estimations show significant values of energy adaptability related to thermal conditioning and heating.

The security of the energy system has also been addressed by Lüking and Hauser (2011). These authors advocate that for the achievement of the expected emission cuts and the assurance of energy supply, it is essential to replace the consumption of fossil fuels with electricity. Furthermore, they argue for the suitability of considering buildings, not exclusively as consumers, but as an integral part of the energy supply system. In order to back these views, the authors carried out calculations of the storable heat in the thermal mass of residential buildings in Germany. They concluded that the thermal capacity of the building mass of these constructions would be enough to take advantage of surplus electricity produced from renewable sources in the future.

Heilek (2015) also studied the case of Germany. In his dissertation, he concluded that an increasing and coordinated use of electricity-based systems to meet heating and cooling needs, combined with thermal storage elements, would lead to a more economical coverage of the thermal demand, also linked to lower GHG emissions. In addition, Heilek pointed out that this would favour the reduction of electricity supply costs and would limit the need to incorporate additional systems into the grid for the storage of electricity.

The study of the consequences of using the thermal storage potential of the building stock on the development of the German electrical system constitutes the main objective of a research project by Dornmair et al. (2017). Their work shows that the CO_2 emissions per unit of electrical energy produced in 2050 would decrease in Germany, given a total coverage of the heating demand of the building and tertiary (offices) sectors by thermal systems based on electricity. The calculations contemplate a proportion of 80% renewable energy in electricity production by mid-century. These results are based on a comparison with those obtained from the analysis of another scenario, in which the use of gas and other fuels predominate in the coverage of the thermal needs of the mentioned sectors. The methodology used in the project consists of the interaction of several types of simulations and optimization models. On the one hand, models of representative objects of the building stock are elaborated by using the software *TRNSYS* to simulate their thermal behaviour. On the other hand, a second model created by using the software *LabView* integrates the thermal installations of buildings and a regulation tool. Finally, *IMAKUS*, developed by Kuhn (2012) in his dissertation, constitutes the third type of model used in the study. This tool is capable of representing and economically optimizing the long-term development of the electrical system configuration.

3.2. *Use of the thermal storage capacity of the building mass for DSM*

Within this field, Bukvić-Schäfer (2008) highlighted in her work the importance of analysing of the use of the thermal storage capacity of the building mass to adapt the energy demand, not under fixed conditions of internal and external temperature, but in a dynamic regime. In this context, the author studied the transmission of heat through external walls of different energy standards in Germany. Mathematical calculations were used, where the variable *room temperature* was modified over time. By implementing a curve of variable price of electricity, it was shown that, owing to the buffering effect of the thermal inertia of the wall, it is possible to adapt the operation of the thermal installations to reduce the energy bill. Nevertheless, the results also reflect that this would lead to a higher overall energy consumption.

Arteconi et al. (2014a, 2014b) also analysed by means of calculations in a dynamic regime up to three strategies for the regulation of thermal equipment, using simulation models in TRNSYS. These strategies were respectively based on reducing demand peaks (*peak-shaving*), interrupting the consumption of electricity following sporadic requests of the grid (*random-request*), and shifting the consumption to night-time (*night-shifting*). Their first study focussed on multi-family residential buildings located in Italy, considering different thermal systems and analysing three representative constructive standards which differ from those of constructions built without implementing any regulation on energy saving. The second study focussed on an office building of a highly energy-efficient standard, with thermally activated constructive elements, and located in Belgium. This work has shown that the type of DSM strategy influences the design of the heating and cooling installation. The higher the energy efficiency of the building envelope and the shorter the time that the electrical consumption needs to be shifted, the more possibilities there would be to manage the demand exclusively with the thermal mass, removing the need for thermal storage tanks, which also tend to increase the total energy consumption of the entire system, according to the results. This indicates that the use of the construction mass to adapt the consumption of the thermal installations might make it possible to simplify the configuration of the general installation and the corresponding transformation of the buildings in order to enhance their interaction with the electrical system. Arteconi et al. (2014b) also concluded that buildings with high energy efficiency (nearly-zero-energy) have no relevance from the point of view of DSM within a *smart grid*, due to their higher independence from the energy supply network.

In their study on the energy flexibility of single-family houses in Denmark, Le Dréau and Heiselberg (2016) also addressed the influence of the energy standard on DSM. To this end, they compared the energy performances of a house from the 80s and a passive house. In this case, one variant based on a radiator system and another considering a radiant floor were defined. Two DSM strategies were taken into account in this study, *heat storage* and *heat conservation*. These strategies are based on the increase and reduction, respectively, of the set-point temperature by two degrees Celsius. The authors concluded that differences in energy standard, in terms of the greater autonomy of the passive house, compared to the less energy-efficient house, are relevant in order to properly control the DSM strategies and to maintain thermal comfort.

On the other hand, Jungwirth (2014) developed in his dissertation a predictive control tool for thermal systems regulation, and combined it with a simulation model in *TRNSYS* through the software *LabView*. This model is based on an office located in Germany, with an energy standard corresponding to current regulations, and with thermally activated floors and ceilings. The function of the control tool is to optimize the DSM within the building considering information related to weather forecasts, energy prices and indoor thermal comfort conditions. This work shows that, by making use of the thermal mass it is possible to flexibly use the thermal systems while preserving the user's comfort. Furthermore, the results also support the conclusions on the possibility of reducing energy bill costs through DSM, put forward in the study by Bukvić-Schäfer (2018).

Reynders et al. (2013) also contributed to the study of the use of this resource. However, they applied a different approach, addressing its use for a smaller scale energy system. This corresponds to the set formed by an individual architectural object (building), including its thermal facilities, and a photovoltaic system for self-consumption. The authors of this study analysed the effect of the thermal properties of the building mass on a type of DSM focused on maximising the use of the photovoltaic system and, therefore, also the use of renewable energy. For this purpose, a representative single-family house in Belgium was used as a case study, on which various simulation models were applied by using the software *Modelica*. Three levels of thermal insulation of the envelope were considered, corresponding to three energy efficiency standards included in the current local regulations. Additionally, one version with massive materials and another based on light materials with lower thermal capacity, were implemented. The analyses assessed the heating period and were carried out using a climatic profile corresponding to the dominant climate in Belgium. Regarding thermal systems, two further variants were defined, which consisted of a heat pump combined with radiators and with under-floor heating, respectively. The results of the research show that not only the provision of a larger thermal storage capacity is relevant to influence energy demand, but the interaction between the thermal mass and the type of thermal system also plays an important role. The different reaction times of the radiators and the under-floor heating bring about the need for managing the demand differently in order to maintain the required comfort conditions. Although the possibilities of increasing the total coverage of energy demand by the photovoltaic system in the studied variants were limited, the authors emphasized that the use of the thermal mass offers a high potential for shifting demand peaks to *valley* times, during which the demand is usually lower than the daily average.

3.3. *Estimation of the DSM potential of buildings*

Regarding the estimation of DSM potentials, among the available approaches it is possible to differentiate methods which make predominant use of information on the amount of installed power from thermal systems. The thermal storage capacity of the thermal mass is not assessed, and the results offer values of the total energy demand of the existing building stock which could theoretically be adaptable for DSM strategies. Examples of this type of estimation are shown in the studies by Klobasa (2007) and Jungwirth (2014).

A second method is based on the calculation of the amount of heat that can be stored in the thermal mass of the building stock. It considers approximations of the composition and dimension of the constructive elements of buildings, and consists of multiplying the corresponding amount of thermal mass by assumed values of its specific heat. This method is applied by Lüking and Hauser (2011) and by Jungwirth (2014) in their studies. Similar to the previous method, this type of estimation neither takes into account the thermal performance of the building mass under dynamic conditions, nor the influence of the type of thermal system used to cover the heating and cooling demand.

The method developed by Hausladen et al. (2014) in their study, encompasses all these points. It was implemented to undertake an estimation of the current DSM potential in Germany. For this, a categorisation of the building stock was performed. This was used as a basis for the selection of representative building types from the tertiary sector (office and commercial buildings) and the residential sector (single-family and multi-family buildings) as case studies. Two energy standards were assessed, a standard corresponding to buildings which have been built under the current regulations, and a low energy efficiency standard, characteristic of constructions built before the introduction of those regulations. For each combination of building type and energy standard, a simulation model was elaborated using the software *IDA-ICE*. These models were used to determine the DSM potential of the different study samples, which were subsequently extrapolated to estimate the overall potential of the tertiary and residential sectors. In this study two DSM strategies were assessed, which involved intentionally switching off and switching on the thermal systems, respectively.

The potentials calculated using this method correspond to the estimated amount of energy that could be managed during the implementation of DSM strategies. This value is determined by mathematically integrating two parameters. The first corresponds to the duration of the DSM strategy. It represents the *time* it takes for the indoor temperature to fall outside the thermal comfort range following the intentional deactivation or activation of the thermal system. This range is delimited by set maximum and minimum temperature values. The second parameter is based on the difference between the thermal *power*, the supply of which can be halted or additionally provided depending on the case at hand, following the initiation of the DSM strategy, and the power that would be required in order to maintain the indoor temperature constant at the original value set at the starting moment of the DSM strategy.

The results from the study by Hausladen et al. (2014) show that the German building stock has an important DSM potential associated with the use of its thermal mass, for intentionally adapting the operation of the thermal systems. Furthermore, the study highlights that the DSM potential depends on characteristic aspects of the buildings, including the energy efficiency of the building envelope, internal loads, the construction system and materials (massive, light), or the type of thermal installation. Thus, it is generally observed that the better the energy standard of the building, the longer the heating system can be deactivated while maintaining comfort conditions, but the lower the energy power that can be switched off as part of a DSM strategy (such as the reduction of peak loads).

Among the conclusions drawn from this study, it should be additionally stressed that the climatic conditions constitute a decisive defining factor for the DSM potential. This was also previously pointed out by Bukvić-Schäfer (2008). Thus, the results show that the DSM potential is different in winter and in summer, and during the day and at night, being higher under moderate climatic conditions and lower under extreme weather situations.

3.4. *Relevant conclusions from the study of the state of the art*

According to the studies described in the previous sections, DSM can assist in the regulation of the electricity supply, favouring a reduction of the economic and technical requirements related to the transition towards an electrical system based on renewable energies. In addition, along with economic incentives and electricity tariffs intended to promote DSM, it would also provide users with the possibility of reducing their energy bill. In turn, this could be harnessed to combat the current phenomenon of energy poverty, which in 2012 affected 54 million people in Europe, according to the study by Pye et al. (2015) commissioned by the EC.

On the other hand, the energy consumption curve of the heating and cooling systems within buildings can be shifted by using the building mass. Its thermal properties allow the operation of these systems to be adapted, while conserving indoor ambient temperature at values within the thermal comfort range. The building stock has an important DSM potential associated with the mentioned adaptability. This potential could be exploited by the electrical system, given a higher level of interaction between the building sector and the power sector, contributing toward achieving the climate goals on reducing GHG emissions.

It can also be stressed that the dimension and characteristic of the DSM potential related to the use of thermal mass would be influenced by the outdoor climate conditions and the constructive features of the building stock. Therefore, extreme climatic conditions lead to lower DSM potentials than moderate situations, and the lower the energy standard of the building envelope, the higher the load that could be shifted in less time.

Based on these findings it can be hypothesised that the DSM potential could vary significantly in the future owing to phenomena related to global warming and the transformation of the built environment. According to the Intergovernmental Panel on Climate Change (IPCC 2013), global warming is expected to affect southern and northern Europe differently. While the climate in the north will become more moderate (increasing the average temperature, especially in winter, where minimal temperatures will also rise, reducing variability), the climate in the south will become more extreme (rising the average temperature, mainly in summer, where the variability will increase due to rising maximal temperatures). On the other hand, the directive 2010/31/EU of the European Parliament determined that by 2020 all new buildings must be *nearly zero-energy* buildings (European Parliament 2010). Nonetheless these buildings might have a low relevance from the point of view of DSM within the smart grid, due to their higher independence from the energy supply network.

Harnessing DSM potential as an additional resource aimed at contributing towards the achievement of the EC climate target on emission cuts, requires that decisions to be made today regarding the transformations of the existing building stock and the future energy system, consider the impact these changes might have on DSM potential in the long run. This may play a particularly decisive role in countries like Germany and Spain, the first and second major producers of fluctuating solar and wind power in Europe, according to official data from the statistical office of the European Union (Eurostat 2016).

However, although there are existing analyses and estimates of the DSM potential of buildings in Europe located in the continental climatic zone, studies of the situation in the Mediterranean climate zone are scarce. The use of different methods and assumptions, limit the comparability of reported findings regarding DSM and its potential in terms of the use of thermal mass, assessed in the abovementioned studies. In addition, none of the addressed cases have included climate data generated according to predictions on the future evolution of climatic conditions in the implemented calculations.

4. Methodological approach

In order to achieve the objectives of the doctoral research project, the application of a combined system of experimental and predictive methods is proposed. Figure 1 shows the structure of the development of this methodology.

The study addresses the comparison of the current and future DSM potential of buildings located in northern Europe, in continental climate, and buildings located in the south, in Mediterranean climate. This comparative study will enable the contrasting of the size and characteristics of the DSM potential in these regions, whose particular climatic conditions lead to differences in terms of energy demand for

heating and cooling in buildings with similar constructive characteristics. The selected case studies are the building stock in Munich (Germany) and in Seville (Spain), which are considered as examples of continental and Mediterranean climate locations, respectively. The research will focus on buildings belonging to the residential sector. According to the EC, this sector is responsible for the highest level of energy consumption for heating and cooling (European Commission 2017b). The co-supervision of this work by TUM and US, provides a favourable framework for the analysis of the residential buildings in the mentioned locations and, overall, for the satisfactory development of the research project. It should be noted that the doctoral research presented in this article builds upon work previously carried out in the studies by Hausladen et al. (2014) and Dornmaier et al. (2017).
Based on the information in section 3.4 it can be hypothesised that in the future, the DSM potential of the building stock related to the use of thermal mass will drastically vary owing to global warming, with different regions of Europe being differently affected. Due to the moderation of the climate in the continental area, the DSM potential of the existing residential stock in Munich will increase in winter and will remain almost unchanged in summer. In Seville, the DSM potential will diminish during the entire year, due to the climate in Mediterranean zone becoming more extreme. In turn, a transformation of the building stock according to current institutional guidelines would lead to a critical reduction of these potentials, due to a reduction of its energy demand and, therefore, its capacity to influence the electricity system.

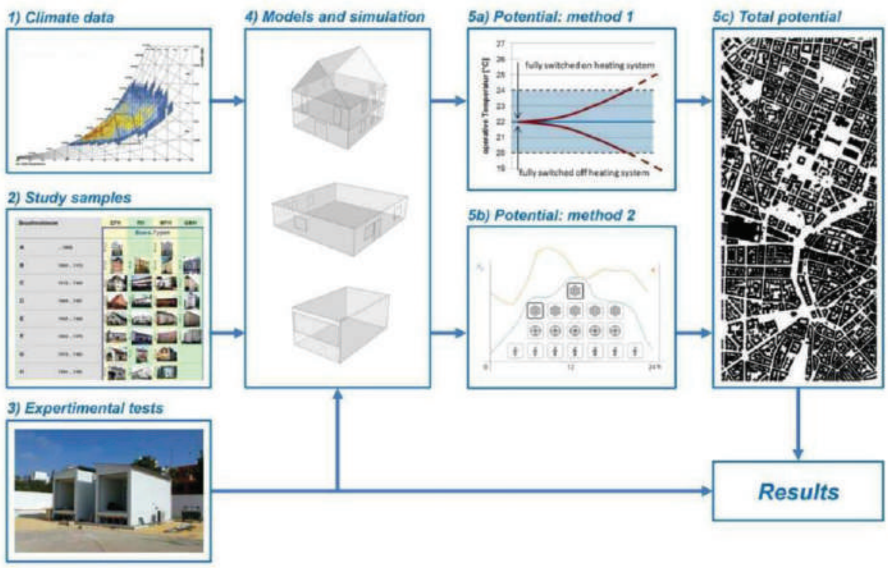

Fig. 1 Outline of the development of the methods proposed for the doctoral research.

4.1. *Collection and analysis of climate data*

The use of *Meteonorm* is planned for the collection of climate data. This tool includes a database with detailed information on climate parameters for various geographical locations. The software also provides predictions of the evolution of climatic parameters from 2020 up to 2100, in 10-year period leaps. These predictions are based on the scenarios of GHG emissions defined by IPCC (2013). In this research, data on temperature, humidity, solar radiation, wind velocity and wind direction are to be considered. The analyses will focus mainly on the current and estimated climate situation for the years 2020, 2050 and 2100.

4.2. *Definition of the study samples.*

The analysis of the building stock of Munich and Sevilla is expected to provide the basis for the definition of the study samples. This analysis involves the identification of residential buildings, which afterwards are to be grouped by typologies and further classified by building age, energy-efficiency-related regulation and current state (original or retrofitted). The study samples will encompass the most representative residential typologies. The definition of their constructive and technical characteristics is based on the use of the dataset developed in the framework of the European project

IEE-TABULA (IEE Project TABULA 2009-2012). In this European study a typological classification of residential buildings in 13 European countries was carried out in order to evaluate their energy performance. The data set contains information on the residential building types in Germany and Spain, analysed by *Institut Wohnen und Umwelt* (Loga et al. 2015) and *Instituto Valenciano de la Construcción* (Madrigal et al. 2016), respectively. It provides a classification of single-family and multi-family buildings, undertaken according to the year of construction and their technical characteristics. In addition to the properties of the building envelope, information on technical equipment is also available, including the most representative thermal systems installed in each case. This dataset was created under common general guidelines, which favours the comparability between the structure of the residential sector in the locations selected for the doctoral research.

4.3. *Implementation of experimental measurements*

In undertaking experimental measurements, the objective is to study the thermal and energetic performance of building components present in the residential typologies assessed in the study samples, under real conditions in a Mediterranean climate. Special attention is to be paid to the heat transfer through different façade solutions and the buffering effect of their thermal inertia on indoor ambient conditions.

The implementation of experimental measurements is based on the use of test cells built within the framework of the CELDA research project carried out at US (TEP130 2015). This project focussed on the retrofitting of social housing in Andalusia, under the assessment of energy performance and indoor ambient conditions. Its main objective was the study and optimisation of façade solutions for the retrofitting of the building envelope. The dimensions of the test cells correspond to a standard building room, present to a large extent in the existing residential typologies in Seville. The cells are equipped with a removable façade, which can be replaced by a different façade solution. Other cell components, walls, ceiling and roof are built similar to a cold room envelope, in order to minimize heat transfer and provide a presumably adiabatic performance. To study the effect of thermal mass on energy demand, different levels of exposed thermal mass should be analyzed. To this effect, massive constructive materials and materials with high specific heat are intended to be attached to the floor and walls.

In addition to the generation of results likely to be of major interest at a scientific level in the research field of the doctoral investigation, the information collected will be used to optimise simulation models and to test their plausibility.

4.4. *Modelling and simulation of the study samples*

The data resulting from the activities described above will provide the basis for modelling and simulating the study samples. To carry this out, the use of *TRNSYS* and *TrnLizard* is intended. *TRNSYS* is a software that allows the simulation of the performance of different system types by dynamic regime calculations. One of the applications of this tool is the energy simulation of models of buildings or building components. *TrnLizard* is a tool which allows combining the dynamic simulations in *TRNSYS* with the analysis of variants under a parametric approach using the *Grasshopper* tool. It can be used to study the thermal performance of living spaces while changing certain parameters, such as the function of the heating and cooling system. The use of this interface is considered for the implementation of a predictive control tool in the simulation of the study samples.

4.5. *Estimation and comparison of DSM potentials*

For the evaluation of the possibilities offered by the thermal mass of the buildings in adapting the operation of the thermal systems, a fundamental requirement to be considered in the doctoral research is the conservation of thermal comfort. The definition of reference ranges based on the values of the technical norm DIN EN 15251 is contemplated. This norm contains recommended values of maximum and minimum indoor temperatures according to building type and system operation mode (heating or cooling). These values represent the limits of the DSM strategies in the analyses.

Two methods of estimating the DSM potential of the study samples are considered. One of these is based on the method applied by Hausladen et al. (2014). It consists of evaluating the maximum duration of the DSM strategy after intentionally switching the thermal systems off or on, and the electricity demand which can be adjusted during this period of time. The other method uses the

studies by Jungwirth (2014) and Reynders et al. (2013) as a reference, and is based on the calculation of the heating and cooling costs and the coverage rate of the electricity demand by renewable energy, taking into account the application of an intelligent regulation of the thermal systems operation. This adjustment is established by the control tool implemented in the simulation models with reference to variable electricity prices and weather forecasts. Thus, the operation of the thermal systems is adapted in order to optimize the cost of the electricity bill. Considering that the higher the rate of renewable energy in the electricity production by the power system, the lower the electricity price, it is possible to establish a relation between the cost of the electricity bill and the coverage rate by electricity generated from renewable sources.
Table 1 summarizes the main steps in which these methods are structured. An estimation of the overall DSM potential of the residential sector of Munich and Seville is intended by extrapolating individual potentials of the study samples to the whole residential stock.

Table 1. Step structure on which the proposed methods for the estimation of DSM potentials are built.

Method 1	
•	Using simulation models, implementation of thermal simulations in dynamic regime, consisting of calculating indoor temperature evolution starting at time when the thermal system is intentionally switched off or on. For each model and each DSM strategy (activation or deactivation), implementation of *one* thermal simulation in dynamic regime for each hour of the analysed year, using that hour as the starting time of the DSM strategy, and using as starting indoor temperature the average value of the maximum and minimum temperature which define the thermal comfort range.
•	Based on the results obtained from the simulations, calculation of the following values:
–	*Time*: maximum possible duration of the DSM strategy, corresponding to the maximum period of time after initiating the DSM strategy, throughout which the thermal system can remain switched off or on until the indoor temperature exceeds the limits of the comfort range.
–	*Power*: difference between the possible thermal power which the thermal system can stop supplying or supply additionally, and the thermal power which would be necessary to keep the starting temperature constant for the maximum duration of the DSM strategy.
•	Using the values calculated in the previous step, calculation for all cases of:
–	DSM potential for each hour of the analysed year by means of the mathematical integration of *Time* and *Power* values.
–	Average value of the potential for heating and cooling periods, and annual average potential.
Method 2	
•	Using simulation models, implementation of thermal simulations in dynamic regime, running the simulation for the entire year being analysed. For each model, implementation of a simulation for each of the following thermal system operation modes:
–	*Standard*: thermal systems operate to keep the starting indoor temperature constant, which corresponds with the average value of the maximum and minimum temperature defining the thermal comfort range.
–	*Optimised*: the operation of the thermal system is regulated by a control tool according to electricity prices, aiming at the optimisation of the cost of the energy bill. In this case, indoor temperature can vary within the thermal comfort range, which is defined between a maximum and a minimum temperature value.
•	From the results obtained in the simulations, estimation of DSM potential based on:
–	Reduction of the energy cost by using operation mode *optimised* compared to *standard*.
–	Reduction of the GHG emission associated with the electrical consumption by using operation mode *optimised* compared to *standard*.
•	Calculation for all cases of the average value of the potential for heating and cooling periods, and annual average potential

5. Conclusions

The analysis of the state of the art shows that the building stock could comprise a certain DSM potential associated with the use of thermal mass, which if exploited for the regulation of the electric system could contribute to the integration of renewable energies and the achievement of the European climate objectives on reducing emissions, both in the building sector and in the power sector.
Using the residential stocks of Munich (Germany) and Seville (Spain) as a case study, a doctoral research project co-supervised by TUM and US is to be carried out, in which the long-term availability of this potential in continental and in Mediterranean climate zones will be analysed. To this effect, an experimental and predictive mixed method is to be applied, considering different scenarios including both climate evolution due to global warming, and transformation of the building stock.
The investigation is based on the presupposition that the DSM potential of the residential sector will rise in continental climate zones and will decrease in the Mediterranean area due to global warming, while a general increase of the share of highly energy-efficient buildings will minimize this potential regardless of their location.

In case the study results confirmed this scenario, these aspects would need to be considered in the planning of the future development of the building sector and the electricity system in Europe. In turn, a revision of the strategies to improve the energy efficiency of the building stock would be advised, as well as the incorporation of alternative and region-specific measures, in order to maintain or even enhance the DSM potential of buildings in the long term.

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