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Design energy flexibility for Italian residential buildings

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ABSTRACT

Having energy flexible buildings is a very important aspect to enable the application of smart demand side management strategies (DSM). DSM is getting more and more relevance in energy systems planning and operation due to the overall increasing energy demand. An energy flexible building is intended to be able to change, in a planned manner, the shape of its energy demand curve, electrical and thermal, while the comfort of the end-users is still guaranteed. The objective of this study is to develop a methodology that allows to classify buildings according to their potential to provide energy flexibility on the basis of their design features. Similarly to the energy performance label, this methodology aims to be a means to extend the energetic characterization of a building also to its energy demand management ability. In this paper the thermal energy demand of buildings (supplied by electrically driven devices, e.g. heat pumps) is mainly taken into account. A quantification method is introduced to estimate the thermal energy demand flexibility. Since the potential to manage the energy demand of a building is strongly influenced by dynamic boundary conditions, "test conditions" have been defined in order to make the method repeatable, not dependent on the specific operational conditions, but more on the design specifications. In this manner the evaluation takes into account only the intrinsic aspects of the building, identified by the construction characteristics and the type of distribution system for the heating and cooling apparatus. Different buildings typologies, representing the most common Italian residential buildings, are considered. The results show a great potential as energy flexibility providers for the latest generation buildings (from 2006 onwards) with a good level of insulation and a radiant system served by a heat pump.

1. INTRODUCTION

The penetration of renewable energy sources (RES) in the generation mix is increasing in the European countries thanks to the Renewable Energy Directive (2009), which sets as target at least 20% of electricity produced from renewable sources by 2020. Thus all European countries have adopted appropriate sustainable energy policies. To date, Italy has already achieved the renewable energy targets for 2020, with a RES share of 17.5% on total energy production in 2015 compared to a goal for 2020 of 17%. Therefore, the new National Electricity Strategy (SEN 2017) considers ambitious but achievable a 27% target of RES production on total energy use by 2030. On the other hand, because of the great diffusion of small and medium renewable energy plants, there is a need for a complete revision of planning and management criteria of the electricity grid. Given the low predictability of renewable sources, one of the biggest challenge of the future is to increase the flexibility of energy networks to improve the reliability of the entire energy system and to make competitive the price of energy. As Lund *et al*. (2015) observed, several solutions could be adopted for this purpose: energy storages, demand side management (DSM), flexible conventional power plants or investments in the modernization of the electricity grid infrastructure. Among these, one of the most interesting solutions is DSM. DSM contains all those policies that aim to influence the customer's energy curve, focusing on changing the shape of the load and thereby helping to optimize the whole power system from generation to delivery, to end use (Faruqui and Chamberlin, 1993). One of the various DSM strategies is Active Demand Response (ADR). It refers to changes in electricity use of end customers from their normal consumption patterns in response to changes in the electricity price over time (Aazami *et al*., 2011). In this context, great interest is given to the residential sector. In Italy, as reported in the new ENEA Energy Efficiency Annual Report, around 40% of national energy use comes from buildings and heating and cooling systems account for about

70% of such energy use (ENEA, 2017). Thus the potential of this sector to provide energy flexibility to the grid is clear.

Several studies available in literature deal with evaluation and quantification of the potential flexibility of Building Energy Systems (BES). Reynders *et al.* (2017a) introduced a method for the generic characterization of energy flexibility of buildings thermal mass. This method consists in the introduction of three indices (available structural storage capacity, storage efficiency and power shifting capability) that allow to estimate the building flexibility performance from the point of view of time, amplitude and cost. The method has been applied to different buildings, introducing a specific ADR event based on an increase in the temperature set-point for a certain period of time. Even Le Dréau and Heiselberg (2016) evaluated the storage potential in building thermal mass. They introduced two modulation strategies, namely heat storage and heat conservation, which correspond respectively to an increase or a decrease of the temperature set-point for a certain time. The quantification of the thermal response of the building is given by the calculation of some indicators: discharged heat, charged heat and shifting efficiency. Stinner *et al.* (2016) introduced a quantification method based on three different flexibility indices: temporal flexibility (forced and delayed), power flexibility and energy flexibility. In this study the authors do not consider only the thermal mass of the building but also an additional thermal storage tank both for space heating and domestic hot water. Klein *et al.* (2017) compared quantitatively the potential to provide energy flexibility by means of different energy storage systems in BES (batteries, fuel switch, water tanks and building thermal mass). In this case the main objective was to evaluate the impact of different grid signals in order to minimize the cost of electricity generation at system level. The quantification was carried out using the minimization of generation costs approach. They used two indices (absolute and relative grid support coefficient) to evaluate the impact of a building on the grid and to estimate the optimization potential for the heating and cooling system.

All the above mentioned works are mainly aimed at studying and quantifying the impact of different ADR strategies for residential buildings. It is evident from these studies that the considered boundary conditions affect the evaluation. In fact, as Reynders *et al.* (2018) observed, the different methods for quantifying energy flexibility so far introduced in the literature are strongly linked to the dynamic boundary conditions, and therefore to the specific moment in which the ADR event occurs.

The main objective of this work is to define a standard methodology for quantifying the energy demand management ability of buildings related to their design specifications, so that they can be classified according to their flexibility performances. With the introduction of this methodology, the aim is to extend the energy characterization of the building to the aspect of energy flexibility. This evaluation can help to understand which features a residential building should have in order to provide energy flexibility and how the demand from different buildings can be aggregated to compose the best mix of end users.

2. METHODS

In this section the method of classification is explained. In order to have a generalized procedure, first of all standard “test conditions” must be defined. In the second section, the flexibility quantification methodology is described. It is based on the building behavior assessment during the response and recovery periods due to an ADR event that switches off the heating/cooling production systems. Four indicators are introduced, which allow an energy flexibility evaluation in terms of time, energy and efficiency. Then, in order to compare buildings, a single parameter is derived from the flexibility indicators: the flexibility performance indicator (FPI). The last section describes the simulation environment used and specify how the simulations have to be performed. The proposed methodology has been applied to typical Italian buildings, in order to provide their categorization.

2.1 Test conditions

Given the influence of boundary conditions on the energy flexibility provided by buildings, standard conditions are defined, called "Test Conditions". They were chosen to take into account the dynamic buildings behavior. For this purpose, the external environment is not assumed as a fixed set of thermo-hygrometric parameters, but a climate file is used in order to model the variability of the external climatic conditions. Obviously, the buildings performance is strictly related to the chosen location.

First of all, the most representative days of summer and winter seasons are identified on the basis of the average daily outdoor temperature. With reference to the Italian norm UNI 10349 (UNI, 1997a), where the climatic data related to heating and cooling of buildings are reported, the average daily temperature values are extrapolated for each month of the year and for each Italian province. The two days per year (for winter and summer) in which the average daily temperature matches better the norm are chosen as representative (in particular for the winter season, January and February are investigated, for summer July and August).

Secondly, an ADR event is applied to the building. The ADR event consists of interrupting power supply to the heating and cooling systems at a specific time. Supposing to address a peak shaving strategy, the time in which the event takes place corresponds to the occurrence of the national peak energy demand. From the observation of the daily balancing data of energy demand and supply, available on Terna website (Terna, 2016), the peak energy demand time is located at 11.00 am for the winter case and at 12.00 am for the summer case in the Italian scenario.

To make the evaluation independent on what happened before the event, it is important that the building is in comfort conditions at the beginning of the evaluation. The selected comfort conditions set an internal temperature set-point of 21°C in the heating season, while in the cooling season the temperature set-point is 23°C with 60% of internal relative humidity.

2.2 Quantification of energy flexibility

This section explains the method to quantify the energy flexibility provided by a building. The method is the same for both summer and winter case. Referring in particular to the method proposed by Reynders *et al.* (2017b), four new indicators have been introduced in this work to represent the building behavior when it tends to the comfort limit conditions. Differently from other works, in this case the heating/cooling system is switched off allowing a temperature set-point reduction/increase of 2°C. Moreover in summer, if the cooling system has an internal humidity control, a 10% increase in indoor relative humidity can be tollerated to remain in the acceptable comfort zone.

The first indicator is the *response time* (t_{res}). It represents the time necessary to the internal temperature to reach the lower or upper comfort temperature bound respectively in winter and summer. This indicator quantifies how much time the thermal generator can remain off, it allows to evaluate the ability of the building and its distribution system to maintain comfort conditions. As soon as the boundary conditions for thermo-hygrometric comfort are reached, the heating or the cooling system has to be switched on. The time required to restore the comfort conditions represents the second indicator, t_{rec} *(recovery time)*. This indicator is related to the response velocity of the distribution system and the thermal inertia of the building. The sum of t_{res} and t_{rec} respresents the total duration of the ADR event (t_{ADR}). Two other indicators have been also used. The first is the *average energy saving* (E_{ADR}), defined as the electric energy saved during the whole ADR event without compromising comfort. The last one is the *ADR efficiency* (η_{ADR}). It is calculated as the ratio between the energy saving achieved during the ADR event (E_{ADR}) and the building electricity consumption in normal operation without ADR events during the t_{ADR} time.

Considering the aspects of time, energy and efficiency, these four indicators make it possible to evaluate the buildings flexibility performance. To be able to make also a classification of buildings, all these aspects have been summarized in a single flexibility parameter, the FPI. The proposed method for estimating the *flexibility performance indicator* is based on the weighted average of four contributions :

1. t_{res} referred to 24 hours, with a weight of 50%,
2. the electricy saving during the response period divided by response duration (t_{res}), referred to the installed rated power, with a weight of 20%,
3. t_{rec} referred to 24 hours, with a weight of 15%,
4. η_{ADR}, with a weight of 15%.

Equation (1) allows the FPI calculation:

$$FPI = \frac{1}{4}\left\{\left[50\cdot\left(\frac{t_{res}}{24}\right)\right]+\left[20\cdot\left(\frac{E_{res}}{\mathrm{P}_{rated}\cdot t_{res}}\right)\right]+\left[15\cdot\left(\frac{t_{rec}}{24}\right)\right]+15\cdot\eta_{ADR}\right\} \tag{1}$$

The weights distribution was assigned to emphasize the impact of the ADR event on the electricity grid. Containing the information of time and power, in fact, the first two contributions refer to the response period in which the heating/cooling systems are switched off and the network can reduce the load. The last two indicators, even if with a lower weight, are to be included as they account for the user's side. The third contribution indicates how quickly the comfort conditions are restored and the fourth considers the actual energy saving that occurs in the case of ADR event. This procedure refers to a dwellings area of 100 m^2 and takes into account the installed electric power. Figure 1 shows the flexibility labels based on the FPI value.

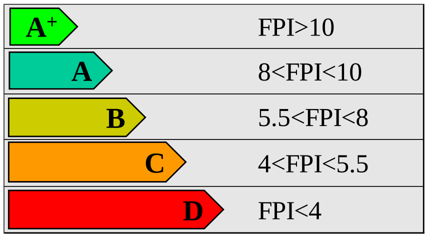


Figure 1: Flexibility performance indicator (FPI)

2.2 Simulation model

The models of the buildings and of the heating and cooling systems have been implemented in a software that allows dynamic simulation of energy transient systems. The simulation time step used is 1 minute. Moreover, in order to be sure that the building is whitin the comfort boundary when the ADR event starts, the simulation is run from the day before and it is pronlonged up to the day after the ADR event, so to have the comfort conditions restored.

3. ITALIAN BUILDING MODELS

The method described in the previous section was applied to a group of Italian buildings representative of different age classes. The main characteristics of these buildings have been extrapolated from the TABULA project (Corrado *et al.*, 2014). In order to evaluate the energy flexibiliity that a building can provide to the electricity grid by means of the thermal inertia in the building enevelope and of the distribution system, every building was equipped with a heat pump, which uses electricity as energy source. For this reason not all the construction classes that are included in the TABULA project are considered, but only those built from 1961 to the present. Indeed in the most recent classes it is possible to install a low temperature distribution system with heat pumps, while in the older buildings (class C5 and C6, covering the years 1961 to 1990) a hybrid heating system, assuming a possible renovation, is present. The following sections provide a description of the implemented models.

3.1 Buildings construction characteristics

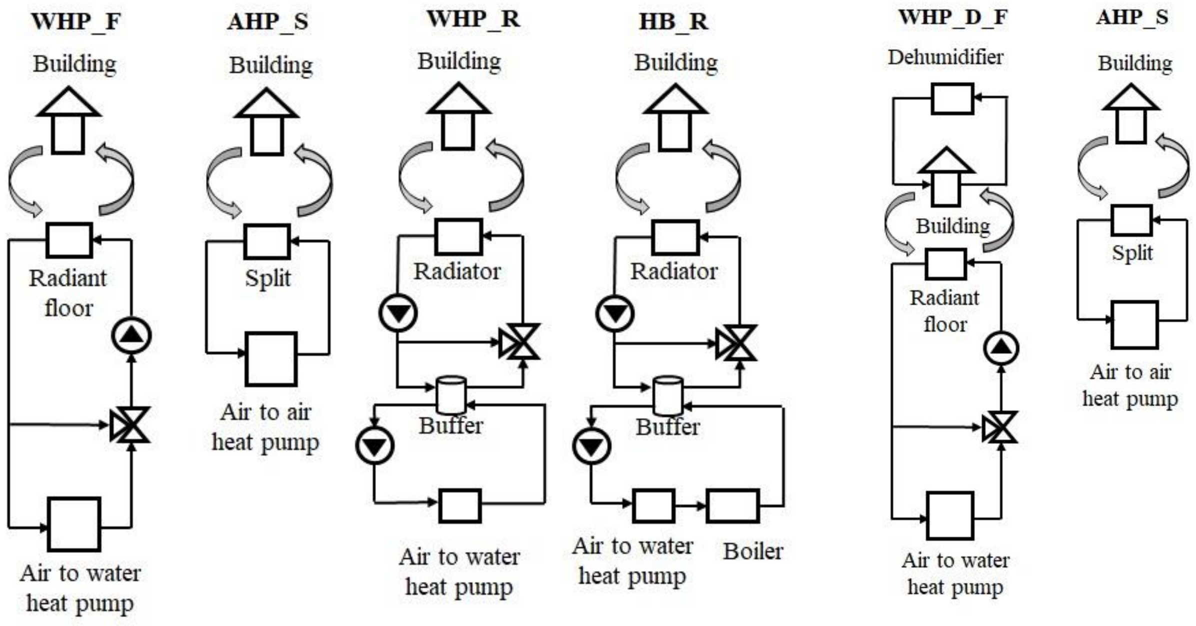
All the dwellings were modelled as composed of a single climatic zone with a living area of 100 m^2 and as apartments in multi-family houses. This type of dwelling represents almost the 70% of all the Italian buildings (Eurostat, 2017). In particular, all the apartments are considered on a raised floor, with a wall and the floor adjacent to another apartment. In all cases, the dwellings are on the top floor of the building. For each wall, 10% of window surface area rate is assumed. The air changes per hour (ACH) are equal to 0.5 h^{-1} for each model. Table 1 shows the values of thermal transmittance (U-value) of the walls of the various models, subdivided according to the construction classes of the TABULA project.

3.2 Heating and cooling systems

As previously mentioned, the heating and cooling systems include an invertible heat pump. In general, four configurations for the heating system and two configurations for the cooling system were modelled (see Figure 2). The heating systems were sized starting from the estimate, in stationary conditions, of the maximum thermal load of the buildings. The evaluation was made considering the outdoor temperature equal to the minimum winter temperature for the chosen location (UNI, 1997b) and an internal temperature of 21°C (comfort conditions). The cooling systems, on the other hand, were sized starting from the estimate of the thermal loads by using the Carrier-Pizzetti technical method (AERMEC,2002).

Table 1: U-value implemented in the models according with TABULA project

Age classes	**$U_{\text{External Wall}}$ [W/m^{2}K]**	**$U_{\text{Internal Wall}}$ [W/m^{2}K]**	**U_{Floor} [W/m^{2}K]**	**U_{Roof} [W/m^{2}K]**	**U_{Windows} [W/m^{2}K]**
C5 (1961-1975)	1.57	1.16	1.09	1.30	5.83
C6 (1976-1990)	0.90	0.90	0.99	0.74	5.68
C7 (1991-2005)	0.60	0.51	0.69	0.53	2.83
C8 (2006-today)	0.29	0.31	0.29	0.28	1.40



(a) (b)

Figure 2: Schematics of the models: (a) heating case, (b) cooling case

This method makes it possible to estimate the summer thermal load (sensible and latent contribution) at different hours of the day, having as data the geographical coordinates, the structure characteristics (mass and thermal transmittance) and the maximum external temperature (UNI, 1997c). The sizing of the system was carried out taking the maximum estimated hourly thermal load.

The heating systems considered are:

1. Air source heat pump with radiant floor distribution system (WHP_F),
2. Direct expansion air source heat pump with split distribution system (AHP_S),
3. Air source heat pump with radiators (WHP_R),
4. Hybrid system with radiators (HB_R).

In the first case, the heat pump, whose performance was derived from a manufacturer catalogue (Viessman, 2016), was sized to cover 70% of the building design power. As can be seen in Figure 2a, by mixing the supply with the return flow rate, the water temperature to the radiant system is maintained constant. In this case, the system is not equipped with an accumulation tank, since the thermal inertia introduced by the floor is sufficient to limit the on-off cycles of the heat pump. This type of system was included in the most recent buildings, in particular C7 and C8 building classes.

In the second case, a heating system with a direct expansion air source heat pump was introduced. In this type of system the refrigerant exchanges heat at the condenser/evaporator directly with the indoor air. In this case the distribution system is made by splits installed on the wall. This configuration was applied both to the C7 and to the C8 age class.

The third heating system was used only in class C7, imagining a small variation of the typical heating systems of buildings of this age (i.e. methane gas boiler and radiators). In a retrofit scenario, an air source heat pump replaces the boiler. The system was equipped with a small thermal storage (a hot water tank of 60 liters), to limit the on-off cycles of the heat pump.

The last type of heating system was designed for the older building classes (C5 and C6) where originally a heating system with boiler and radiators was installed. A retrofit of the heating system is assumed: a heat pump was added to a classic 25 kW boiler, used both for heating and domestic hot water. An alternative-parallel configuration is considered in which the heat pump was sized for an external temperature of 5°C (Klein *et al*., 2014a). When the heat pump is not enough for more extreme external conditions, the boiler steps in providing the additional thermal power required. In this case, the system was equipped with a small thermal storage to limit the on-off cycles of the heat pump (80 liters for class C6 and 100 liters for class C5). The heating system is regulated by means of a compensation curve (Klein *et al.*, 2014b).

Table 2: Main features of the considered models

HEATING CASE				**COOLING CASE**				
Model	**Design thermal loads [kW]**	**Rated capacity heat pump [kW]**	**Rated COP heat pump**	**Model**	**Design thermal loads [kW]**	**Rated capacity heat pump [kW]**	**Rated COP heat pump**	**Rated capacity dehumidifier [kW]**
C8_WHP_F	2.80	2.0	2.38	C8_WHP__D_F	3.03	2.2	2.98	2.5
C8_AHP_S	2.80	2.8	2.45	C8_AHP_S	3.03	2.8	2.35	-
C7_WHP_F	4.30	3.0	2.38	C7_WHP_D_F	3.71	2.4	2.98	2.5
C7_WHP_R	4.30	3.8	2.01	C7_AHP_S	3.71	3.5	2.35	-
C7_AHP_S	4.33	4.0	2.45	C7_AHP_S	3.71	3.5	2.35	-
C6_HB_R	4.21	4.0	2.62	C6_AHP_S	4.08	4.0	2.35	-
C5_HB_R	6.09	6.0	2.62	C5_AHP_S	4.27	4.3	2.35	-

As far as the cooling system is concerned, two types of configurations were modelled (see figure 2b):

1. Air source heat pump and dehumidifier with radiant distribution system (WHP_D_F),
2. Direct expansion air source heat pump with split distribution system (AHP_S).

Only the most recent dwellings (C7 and C8) were modelled with the first type of cooling system. In this configuration the same heat pump used in the heating case reverses its operation and sends chilled water to the distribution system. The heat pump is sized to cover only the amount of sensitive heat that must be removed. The treatment of latent heat is entrusted to an internal air humidifier. In this way it is possible to control both the internal temperature and relative humidity.

The second type of cooling system has the same characteristics as the direct expansion air-to-air heat pump used in the heating case. In this case the same unit treats both the sensitive and the latent heat, so the heat pump was therefore sized to cover the overall thermal load. In this case it is possible to control only the internal temperature. This configuration was coupled to all the construction classes: C5, C6, C7 and C8.

Table 2 summarizes the main characteristics of the models.

4. RESULTS AND DISCUSSION

In order to classify the buildings on the basis of their ability to be energetically flexible, the procedure explained in section 2 has been applied to a group of buildings with the characteristics described above. All the models have been located in the city of Ancona (43°35′39″ N, 13°30′12″ E), in central Italy.

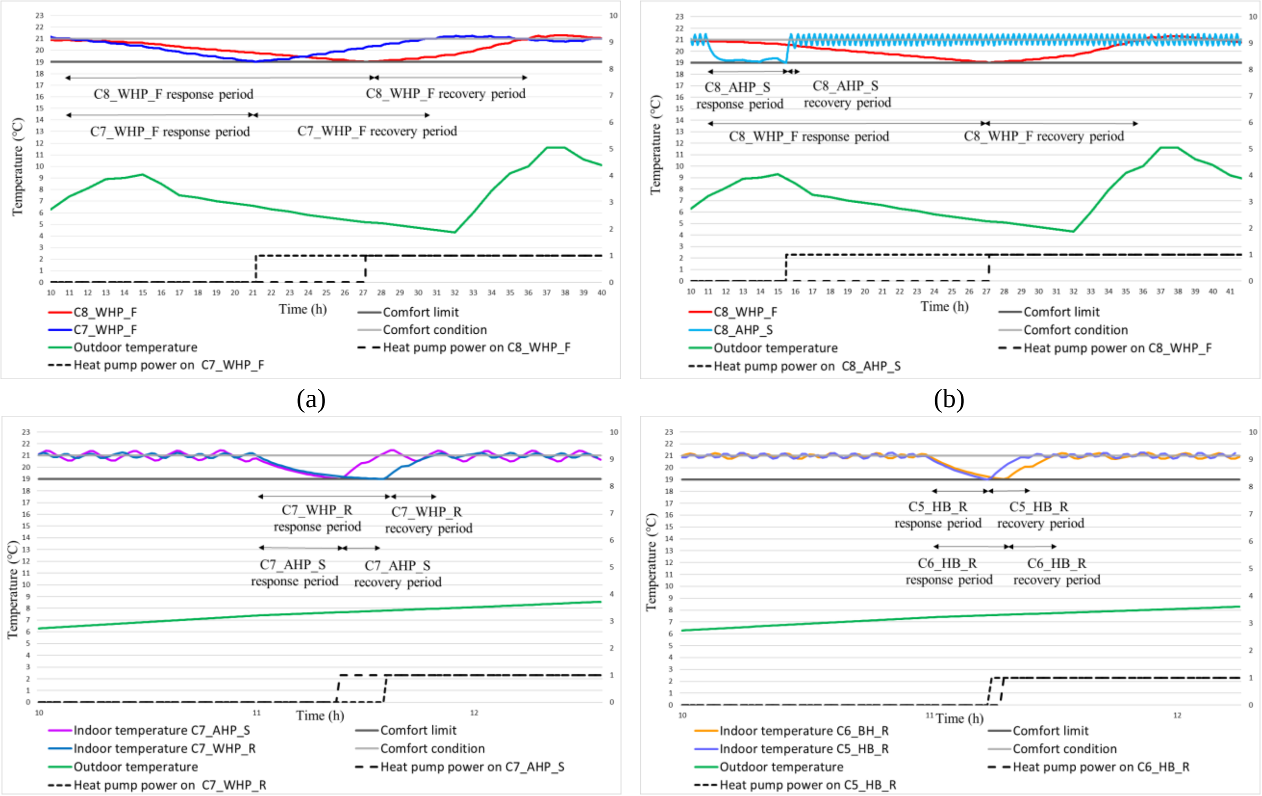
The representative winter day is January 18. The average daily temperature obtained from the climate file is 6°C when the average monthly temperature for the month of January for the city of Ancona indicated in the norm is 6.3°C (UNI, 1997d). In the summer case, the representative day considered is July 11. In this day the average daily temperature is 24.5°C when the standard indicates to consider a temperature of 24.4°C (UNI, 1997e).

Table 3 shows the results for the application of the methodology to the heating case. As expected, the model with the greatest potential to provide energy flexibility is the one with a more recent age class, therefore with an excellent level of thermal insulation and equipped with a radiant floor as distribution system. On the other hand, the model with the worst performance is the older one equipped with radiators.

Regarding the same type of heating system (WHP_F), for model C8 the duration of the ADR event is 25.04 hours while for model C7 it is 23.38 hours. The difference between these two models is mainly due to the t_{res} indicator.

Table 3: Evaluation of energy flexibility in heating case

Model	**t_{res} [h]**	**t_{rec} [h]**	**t_{ADR} [h]**	**E_{ADR} [kWh]**	**η_{ADR}**	**FPI**	**Flexibility label**
C8_WHP_F	16.15	8.89	25.04	0.94	0.13	11.84	A+
C8_AHP_S	4.48	0.24	4.72	1.82	0.88	7.59	B
C7_WHP_F	10.18	13.20	23.38	1.18	0.11	9.62	A
C7_WHP_R	0.60	0.23	0.83	0.29	0.59	4.58	C
C7_AHP_S	0.38	0.19	0.57	0.17	0.41	3.72	D
C6_HB_R	0.30	0.20	0.50	0.26	0.68	4.19	C
C5_HB_R	0.25	0.18	0.43	0.22	0.44	3.23	D



(a) (b)

(c) (d)

Figure 3: Comparisons of the result simulations, (a) comparison between C8_WHP_F and C7_WHP_F, (b) comparison between C8_WHP_F and C8_AHP_S, (c) comparison between C7_AHP_S and C7_WHP_R, (d) comparison between C6_HB_R and C5_HB_R

This fact highlights how a better level of thermal insulation (as for C8_WHP_F) allows to obtain a greater inertia in the thermal response. Then it is translated into the building ability to maintain the conditions within the comfort zone for a longer period (see Figure 3a). The t_{rec} indicator differs slightly between the two models and it is 8.9 hours for C8_WHP_F and 13.2 for C7_WHP_F. The great thermal inertia of the distribution system affects the most the recovery phase. The quantity of energy saved is about 0.94 kWh for the C8 class and about 1.18 kWh for the C7 class. From the observation of the last indicator, η_{ADR}, it can also be noted that it assumes relatively low values, 13% for C8_WHP_F and 11% for C7_WHP_F. This is due to the great energy consumption in the recovery phase that makes the actual energy saving lower. With regard to the other models, an overall decrease of t_{res} is observed compared to the two cases discussed so far. It mainly depends on the almost total absence of thermal inertia introduced by the other distribution systems. So, the t_{res} indicator depends almost entirely on the thermal storage of the building structure. With the same construction class, for example C8, the indicator t_{res} decreases by 72% if the building is equipped with a direct expansion heating system rather than with a radiant floor system. A very consistent variation is obtained for class C7 too. In this case t_{res} falls by 94% if the radiant floor system is compared with the radiators. A pretty larger decrease occurs with the direct expansion system, about 96%. These results highlight the influence of the distribution system thermal inertia. However, it can be observed that class C8 (C8_WHP_F and C8_AHP_S) allows to obtain always good values for the flexibility indices. Another observation can be made by looking at the results obtained for the C7_WHP_R and C7_AHP_S. Since the models belong to the same age class, the difference observed in the t_{res} indicator is due to the distribution system. Although small, in fact, radiators have a thermal inertia greater than splits, this allows C7_WHP_R to take a longer time than C7_AHP_S to reach the comfort limit condition. These types of distribution systems (radiators and splits) however, show lower values of energy saving (E_{ADR}) compared to the radiant floor but their ADR efficiency is greater, 59% for C7_WHP_R and 41% for C7_AHP_S.

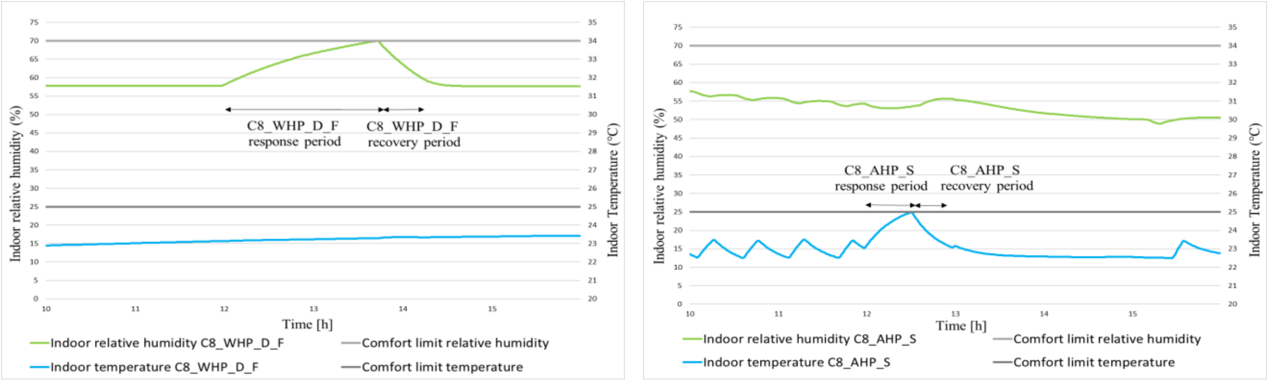
Table 4: Evaluation of energy flexibility in cooling case

Model	**t_{res} [h]**	**t_{rec} [h]**	**t_{ADR} [h]**	**E_{ADR} [kWh]**	**η_{ADR}**	**FPI**	**Flexibility label**
C8_WHP_D_F	1.73	0.50	2.23	0.83	0.60	6.18	B
C8_AHP_S	0.52	0.37	0.89	0.43	0.41	5.24	C
C7_WHP_D_F	1.53	0.54	2.07	0.73	0.55	6.00	B
C7_AHP_S	0.57	0.31	0.88	0.36	0.45	5.04	C
C6_AHP_S	0.50	0.27	0.77	0.29	0.35	5.12	C
C5_AHP_S	0.48	0.25	0.73	0.36	0.44	4.80	C

The reason behind is mainly due to the velocity in response of these heating systems, as shown by the second indicator t_{rec} that is 0.23 hours for C7_WHP_R and 0.19 hours for C7_AHP_S (see figure 3c).

Regarding the models of older age classes (C6 and C5), in which there is a low level of thermal insulation in class C6 and not at all in class C5, a hybrid heating system with radiator distribution was introduced. As for the direct expansion system, in this case the flexibility time indices are greatly influenced by the low thermal inertia of the system (see figure 3d). Focusing on this type of heating system, it can be observed that relatively low values of flexibility indices are obtained. The duration of the ADR event is 0.50 hours with an energy saving of 0.26 kWh for class C6, while for class C5 the event takes 0.43 hours with a value of E_{ADR} of 0.22 kWh. It can be observed that these indices are however comparable with those obtained for C7_WHP_R. This allows to conclude that without excellent levels of thermal insulation and thermal inertia, the energy flexibility achievable from buildings is limited.

Table 4 shows the flexibility indicators obtained for the cooling case. From a first observation of the results, the WHP_D_F system (applied only to the most recent construction classes: C7 and C8) has the best performance in terms of energy flexibility among the considered cases. Indeed the ADR event lasts about 2.23 hours for class C8 and 2.07 hours for class C7, with an energy saving of 0.83 kWh for C8_WHP_D_F and of 0.73 kWh for C7_WHP_D_F. In these models, as already mentioned, it is possible to control the humidity of the indoor air too. The t_{res} indicator is so evaluated with the comfort limit condition reached earlier, between temperature and humidity. In the specific case, the boundary condition for humidity is reached faster (see figure 4a). In general the E_{ADR} indicator accounts therefore for both the heat pump and the dehumidifier consumption but, for both the models, C8_WHP_D_F and C7_WHP_D_F, only the dehumidifier is taken in account since the heat pump remains off during the test day (even without the ADR event). As far as the other cooling system is concerned, all the dwellings are modelled with it. Figure 4 shows the temperature and internal humidity trend during the ADR event for class C8 models (the trends are similar for the other classes with the same cooling system). Considering all the modelled age classes, from C5 to C8, ADR events have a duration ranging between 0.73 hours and 0.89 hours. Also the energy saving during the ADR event has similar values among the various cases (from 0.29 kWh to about 0.43 kWh). This behavior makes possible to conclude that, for the modelled dwellings in summer period there is a lower overall capacity to provide energy flexibility (even if for the older C5 and C6 models, the flexibility indicators assume a slightly higher value for cooling than for heating). Furthermore, there is a small influence of the structural composition of the building in case of reduced thermal inertia of the distribution system. In Italy, however, where the air-conditioning market is growing strongly (+ 28% from 2015 to 2016 according to a statistical survey by Assoclima (2017)), having energy-flexible buildings will be very important especially in the summer season.



(a) (b)

Figure 4: Comparisons of the result simulations in cooling case, (a) C8_WHP_D_F, (b) C8_AHP_S

A possible solution could be an additional thermal energy storage coupled to the cooling system. About this, many works are available in the literature (Li *et al*., 2012). Moreno *et al*.(2014) have studied the load shifting capability of two thermal energy storages (a water tank and phase change materials (PCM)) coupled with a heat pump, for cold storage in building for space cooling. They have found that the performance of these systems is very good, in particular their results highlight that the PCM tank is able to supply 14.5% more cold and to maintain the indoor temperature within comfort 20.65% longer than the water tank.

Eventually, it is important to underline that, due to the many assumptions and approximations that should be made, it is advised against the use of a stationary method for the evaluation of energy flexibility, especially in cooling case. Assuming, for example, for the indoor temperature the comfort one and the daily average temperature indicated by the standard (UNI, 1997f) for the external environment, the stationary estimate of t_{res} could be done by evaluating the time necessary to heat up (or cool down) 2°C the room air mass. The losses through the walls in stationary conditions would be fixed and the external gains would be constant. The same approximation would occur in the subsequent recovery phase. However, especially for long events, it would be misleading to neglect the variations of the boundary conditions.

5. CONCLUSIONS

This study provides a methodology for classifying buildings from the point of view of their ability to be energy-flexible. This method takes into account the buildings intrinsic thermal features: construction characteristics and thermal inertia of the distribution system.

Summing up, for a given building, this method can be applied according to the following main steps:

1. Identification of the representative day for winter and summer by matching data on the Norm and the climate file representative of the geographic location;
2. Identification of the starting time for the ADR event (peak power demand on the electricity market);
3. Modelling of the building and its heating and cooling system with a transient simulation tool;
4. Simulation (with 1 minute time step) of the model in normal operation to obtain the reference condition (the simulation must start 1 day before the representative day);
5. Simulation of the building during the ADR event;
6. Evaluation of the flexibility indicators: t_{res}, t_{rec}, t_{ADR}, E_{ADR} and η_{ADR};
7. Calculation of the FPI.

In this work the method was applied to different types of residential buildings both for summer and winter case, imagining the presence of heating/cooling systems driven by electricity. The results show a great influence of the distribution system in the evaluation of the flexibility indicators, especially in the heating case. The radiant floor distribution system has a good level of thermal energy storage and can maintain for long periods the comfort (from 10 to 16 hours for buildings with an increasing level of insulation). Also the building envelope features play an important role. The models with a better level of insulation show a better ability to maintain comfort, especially in heating case. As far as cooling is concerned, the analysis led to the conclusion that, if the system consist of a radiant floor and a dehumidifier, good performance can be achieved in terms of flexibility. However, in the most widespread case of direct expansion cooling systems, buildings do not have a great capacity to provide flexibility if not equipped with a thermal energy storage.

NOMENCLATURE

t_{res}	response time	(h)
t_{rec}	recovery time	(h)
t_{ADR}	ADR duration	(h)
E_{ADR}	average energy saving	(kWh)
η_{ADR}	ADR efficiency	(-)
P_{rated}	installed rated power	(kW)
E_{res}	energy saving during response period	(kWh)
FPI	flexibility performance indicator	(-)

REFERENCES

Aazami R., Aflaki K., Haghifam M.R. (2011). A demand response based solution for LMP management in power markets. Power Energy Syst, 33, 1125-1132.

AERMEC. (2002). Rel 02. I carichi termici estivi. In Italian.

Assoclima, costruttori sistemi di climatizzazione. (2017).In Italian. Retrieved: http://www.expoclima.net/focus/mercati/climatizzazione_mercato_italia_in_crescita_28_per_cento_nel_2016_indagine_assoclima.htm.

Corrado V., Ballarini I., Corgnati S.P., Politecnico di Torino-Dipartimento di Energia, Gruppo di ricerca TEBE. (2014). Building Typology Brochure-Italy, in Italian.

ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile). (2017). Energy Efficiency Annual Report. In Italian.

RAEE2017 Rapporto annuale efficienza energetica, in Italian. Retrieved http://www.efficienzaenergetica.enea.it.

European Parliament, 23April 2009, Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.OJ L 140, 5.6.2009, p. 16–62. Retrieved http://data.europa.eu/eli/dir/2009/28/oj.

Eurostat. (2017). Statistiche sulle abitazioni ,in Italian. Retrirved: http://ec.europa.eu/eurostat/statistics-explained/index.php/Housing_statistics/it.

Faruqui A., Chamberlin J.H. (1993). Principles and Practice of Demand-side Management, EPRI.

Klein K., Herkel S., a, Henning H.M., Felsmann C. (2017). Load shifting using the heating and cooling system of an office building: Quantitative potential evaluation for different flexibility and storage options. *Applied Energy* 203, 917-937.

Klein K., Huchtemann K., Müller. (2014). Numerical study on hybrid heat pump system in existing buildings. *Energy and Buildings*, 69, 193-201.

Le Dreau J., Heiselberg P. (2016). Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy, 111, 991-1002.

Li G., Hwang Y., Radermacher R. (2012) Review of cold storage materials for air conditioning application. *International journal of refrigeration*, 35, 2053-2077.

Lund P.D., Lindergren J., Mikkola J., Salpakari J. (2015). Rewiew of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew Sust Energy*, 45, 785-807.

Ministero dello sviluppo economico, 2017, Strategia Elettrica Nazionale SEN 2017, in Italian. Retrieved http://www.sviluppoeconomico.gov.it/index.php/it/energia/strategia-energetica-nazionale.

Moreno P., Castell A., Solé C., Zsembinszki G., Cabeza L.F.. (2014). PCM thermal energy storage tanks in heat pump system for space cooling. Energy and Buildings, 82, 399–405.

Reynders G., Diriken J., Saelens D. (2017) Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. *Applied Energy* 198, 192-202.

Reynders G., Lopes R.A., Marszal-Pomianowska A., Aelenei D. , Martins J., Saelens D. (2018). Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. *Energy & Buildings*, 166, 372–390.

Stinner S., Huchtemann K., Müller D. (2016). Quantifying the operational flexibility of building energy systems with thermal energy storages. *Applied Energy* 181, 140-154.

Terna. (2016). In Italian. Retrieved. http://www.terna.it/it-it/sistemaelettrico/dispacciamento/datiesercizio/datigiornalieri.aspx.

UNI, Ente Nazionale Italiano di Unificazione. (1997). Riscaldamento e raffrescamento degli edifici Dati climatici, in Italian. UNI 10349:1994/EC:1997.

Viessman. (2016). Vitocal 222-S – Pompa di calore aria acqua split con tecnologia DC inverter per riscaldare e raffrescare, in Italian. Retrieved: http://downloads.viessmannitalia.it/documentazione/vitocal/vitocal-222-s242-s/.

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