Design Optimization of Energy Flexibility for Residential Buildings

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Abstract

Due to its progressive aging, the need to plan a long-term renovation strategy for the European building stock is increasingly urgent. Furthermore, the growing penetration of discontinuous and non-programmable renewable energy sources asks for an adaptable demand to the supply variability. Thus, the realization of new buildings which are both efficient and energy flexible can be a way to increase reliability and security of the current energy grid. Purpose of this work is to characterize the effect of different buildings renovation strategies on their energy flexibility performance obtained through electric heating energy demand management. The energy flexibility is quantified by means of a single indicator: the Flexibility Performance Indicator. As the Energy Performance Certificate, it is calculated with a standardized procedure. In this work, starting from a low energy performance reference building, the energy flexibility performance obtainable with different energy efficiency interventions is assessed. Eventually the extent of the requested investment combined with the potential electricity costs saving derived from it is evaluated.

Introduction

Currently in Europe buildings are responsible for approximately 40% of energy consumption and it is estimated that almost 75% of them is energy inefficient (European Commission, 2018). With the Directive 2012/27/EU (European Parliament, 2012), European countries will have to develop long-term national strategies to support the renovation of public and private buildings in order to obtain a decarbonised and energy efficient building stock by 2050. To achieve this goal, the directive 31/2010/EU (European Parliament, 2010) suggests buildings transformation into Nearly Zero Energy Buildings (NZEBS).

Furthermore, the high penetration of Renewable Energy Sources (RES), whose nature is discontinuous and non-programmable, combined with the growing electricity demand (e.g. diffusion of electric vehicles, air conditioning systems, heat pumps (IEA, 2017)), ask for a solution to guarantee a secure operation of the energy system. Having a building stock both efficient and flexible can contribute to rely on a large demand share adaptable to the supply variability.

The concept of energy flexible building (EFB) is introduced by IEA EBC Annex 67 (Jensen et al., 2017).

They defined an EFB as “a building able to manage its demand and generation according to local climate conditions, user needs and energy network requirements”.

Due to the strong dependence to the boundary conditions and uncertainty on evaluation, energy flexibility quantification in buildings is one of the topics of greatest interest in current scientific production (Reynders et al., 2018). Reynders et al. (2017), for example, introduced a simulation-based method for the generic characterization of energy flexibility of buildings thermal mass through the introduction of three indicators: available structural storage capacity, storage efficiency and power shifting capability. Also Stinner et al. (2016) introduced a quantification method based on three different flexibility indicators: temporal flexibility (forced and delayed), power flexibility and energy flexibility. From the simulation of opposite events (charge and discharge), they evaluate the energy flexibility of buildings heating systems with thermal storage tank used both for space heating and for domestic hot water.

These methodologies are closely related to the evaluation of the energy flexibility potential of buildings in operational scenarios. However, to characterize the flexibility impact of building renovation strategies a design approach must be used. Mugnini et al., 2018 introduced a methodology which allows the calculation of a single indicator, the Flexibility Performance Indicator (FPI), able to quantify the flexibility in reference conditions and rate buildings accordingly.

Purpose of this work is to provide guidelines for buildings design (new constructions or renovations) aimed at improving the energy flexibility derived from the management of their thermal demand (supplied by means of electric heating systems, i.e. heat pumps). The FPI methodology is used to quantify the energy flexibility that can be obtained under given boundary conditions. In particular the effect of varying the building thermal properties on energy flexibility is assessed.

Methods

The energy flexibility quantification is realized with the buildings flexibility labelling method proposed by Mugnini et al., 2018 and extended in the paper by Arteconi et al., 2019. It is simulation-based and requires a transient building simulation tool. Indeed, the building energy demand strongly depends on external environment conditions variability, on the dynamics of its thermal response and on the instant needs of the grid (Reynders et

al., 2017). For this reason, the choice of standard boundary conditions (SBC) is necessary to compare the flexibility performance of different buildings.

This work focuses mainly on buildings renovation since, at present, in Italy (GreenReport.it, 2019) it is estimated that the share of energy inefficient buildings (class G) is about 56%. Starting from a building with constructive characteristics of 1975, the effect of different energy refurbishment interventions, such as thermal insulation of the building envelope or windows replacement on building flexibility performance is evaluated. Being the energy flexibility provided to the electricity grid of interest in this analysis, heat pumps are considered as heating systems.

Since the potential economic impact deriving from the participation in DR programs is the best incentive for a final user, an attempt to quantify the possible economic benefit is introduced.

Energy flexibility quantification method

The energy flexibility of the buildings is quantified by the calculation of the FPI (Mugnini et al., 2018). Its formulation derives from the evaluation of four flexibility parameters (the response time, the committed power, the recovery time and the actual energy variation) which include all the buildings energy flexibility typical aspects: time, (i.e. duration), capacity (amount of energy that can be shifted per time unit) and power (Reynders et al., 2017). Since it is calculated in design conditions and with established SBC, the FPI allows the labelling of buildings in flexibility classes in the same fashion as the energy performance label. As suggested by Jensen et al. (2017), FPI is formulated by assessing buildings ability to deviate from a reference standard operation if an external incentive would be provided.

In order to apply such method, first SBC related to the comfort constraints, the external environment conditions and the demand response (DR) event have to be defined. As proposed by Mugnini et al. (2018), during a DR event the indoor temperature can vary in the comfort range 20-22°C, while a typical meteorological year (TMY) must be considered (Pernigotto et al., 2014) to model the dynamic behaviour of the building under variable ambient conditions. In this work it is obtained through Meteonorm (TESS, 2013).

As far as the DR event is concerned, a peak shaving strategy (PSS) is selected for its importance on reducing the peak energy demand and installed power capacity. It consists of interrupting power supply to the heating systems at the electrical system peak power demand time until the internal comfort conditions reach the lower boundary (response period). Then the heating system is switched on and the event can be considered ended when the initial internal comfort conditions are restored (recovery period). The starting time of the DR event is chosen corresponding with the peak of the National electric power demand. In the Italian scenario, the DR starting time is 7.00 pm (Terna S.p.a., 2019). Figure 1 shows a typical building indoor temperature trend during the DR event participation.

Figure 1: Indoor temperature during the DR event.

Finally, the DR event day must be selected as the most representative day of the winter season. In particular, the average daily temperature values for each month (UNI, 2016b) are considered to extract it from the TMY file.

Once the boundary conditions are defined, a building model must be realized in an energy simulation environment. From the dynamic simulation the indoor temperature trend, the electric power demand and the energy consumption during the DR event can be obtained.

At this point the FPI can be calculated (Mugnini et al., 2018). It depends on four different terms. The first term is the response time t_{res} [hours]. It represents the time necessary to the internal temperature to reach the lower temperature bound. The second one is the committed power $\dot{P}_{res}$ [kW_e], that represents the effect of the DR event in terms of electrical power engaged. It is defined as the integral of the difference between the building reference power demand and its power demand during the DR event divided by the duration of the response phase, t_{res} . As they refer to the response period when the heating system is switched off and then the network load is reduced, these two parameters are more interesting for the electric grid side. The other two parameters, on the other hand, are of greater interest for the user side, because they consider how fast the initial comfort is restored after a DR event and the actual DR impact on energy use. They are: the recovery time t_{rec} [hours], and the actual energy variation E_{DR} [kWh_e], defined as the difference in energy use between the reference condition and the DR event during the whole DR event, t_{DR} . Thus, the flexibility performance indicator is defined in a dimensionless form as weighted average of four contributions, as shown in (1), where the asterisk indicates the dimensionless terms and p_i the contributions weight.

$$FPI = \frac{1}{4} (p_1 \cdot t_{res}^* + p_2 \cdot \dot{P}_{res}^* - p_3 \cdot t_{rec}^* + p_4 \cdot \eta_{DR}) \quad (1)$$

t_{res}^* is the response time referred to 24 hours, with a weight of 60% ($p_1=60$). $\dot{P}_{res}^*$ is the committed power normalized to $\dot{P}_{rated}$ with a weight of 20% ($p_2=20$). t_{rec}^* is the recovery time normalized on 24 hours with a weight of 10% ($p_3=10$). η_{DR} is a sort of DR energy efficiency. Indeed, it is calculated as the ratio between the actual energy variation achieved during the DR event (E_{DR}) and the building electricity use in reference operation during t_{DR} . It has a weight of 10% ($p_4=10$). The weights distribution is determined with an empirical approach by observing results of a large share of buildings

configurations during a DR event. It is assigned to emphasize the impact of the DR event on the electricity grid. Referring to the response period in which the heating/cooling systems are switched off and the network can reduce the load, a greater weight is assigned to the first two parameters. The other two parameters, even if with a lower weight, have to be included as they account for the user's side. In particular the recovery time gives a negative contribution since it represents high flexibility performance with an opposite trend than the others three indicators.

Based on FPI values, a flexibility class distinction can be made as reported in Figure 2.

Figure 2: Energy flexibility classes for building labelling.

Economic evaluation method

As Jensen et al. (2017) highlighted, a successful implementation of energy flexibility strategies strongly depends on the acceptance and motivation of the stakeholders. To demonstrate the potential savings in the electricity bill, a hypothetical electricity tariff designed for users who are interested in participating in DR programs is modelled. During the DR PSS event, we imagine that the user can benefit of a discounted electricity tariff: if the load is interrupted at the peak demand time, during the recovery period, the electricity price is half of the standard constant tariff (i.e. 0.06425 €/kWh⁻¹). Therefore, the DR economic benefit is given by the difference between the cost of electricity use without any DR event and with DR event during the duration of the whole event (t_{DR}).

Simulation Environment

Buildings energy simulations are conducted with TRNSYS 17 (Solar Energy Laboratory, 2012a). The simulation time step used is 1 minute.

In order to evaluate a large number of building renovation configurations, TRNSYS is combined to GenOpt (Wetter, 2011), a generic optimization tool. The algorithm *Mesh* is used, it allows to span a multi-dimensional grid in the space of the independent parameters so to evaluate the objective function (i.e. FPI) at each grid point. In the next section a detailed description of all the considered configurations is provided.

Case study

As reference building is selected a single family house (SFH) belonging to class 5 (1960-1975) of Tabula project

(Corgnati et al., 2016). For Italy Tabula refers to climatic class E (from 2101 to 3000 GG), which represents 52.5% of Italian municipalities (ISTAT, 2011), thus the considered building is located in Milan (45°25' N, 9°16', E2404 GG). It has an area of 100 m² and 10% of window surface area rate was assumed (Italian Ministry of Economic Development, 1975). Its envelope is composed of hollow brick masonry for the external wall, pitched roof with brick-concrete slab, concrete floor on soil and single glass with wood frame. This class of buildings has no thermal insulation in the walls. In Table 1 the envelope thermal transmittances (U-values) are reported. Furthermore, in the model the air changes per hour (ACH) are assumed 0.5 h⁻¹, while the occupancy density is 30 m² per person with a corresponding internal gain of 120 Watt per person and an artificial light density of 10 Wm⁻² (Solar Energy Laboratory, 2012b).

Table 1: Thermal transmittance (U values in Wm⁻²K⁻¹) for the starting reference building and for the most energy performing renovated building.

Building	U _{roof}	U _{ex_wall}	U _{floor}	U _{window}
Starting reference	2.20	1.26	2.00	5.38
Most energy performing	0.24	0.28	0.29	1.40

Starting from this reference building model, different renovation strategies are considered by adding insulation to the external walls, roof and floor respectively and by changing the windows. In particular thermal insulation (thermal conductivity 0.04 Wm⁻¹K⁻¹ and density 30 kgm⁻³) with increasing thickness (1 cm increments) is added to all the opaque structures. The final most energy performing configuration considered is in accordance with values from the Italian regulation for buildings undergone to energy requalification from 2021 (Italian Ministry of Economic Development, 2015). Table 1 shows the related U-values. For the specific case these values are reached with an external wall insulation thickness of 11 cm, a roof insulation thickness of 14 cm and 11 cm for the insulation layer in floor. For windows, argon gas double glazing windows are used.

As regards the heating system, an air to water heat pump (AWHP) is used, since the interest of this work is the evaluation of buildings energy flexibility provided to the electricity grid. The AWHP performance is derived from the manufacturer catalogue (Viessmann, 2016). As distribution system low temperature radiators are used.

Table 2: HP design thermal capacity classes.

Level	Maximum heat load [kW _t]	Minimum heat load [kW _t]	HP design capacity [kW _t]
1	13.2	11.2	12.2
2	11.2	9.2	10.2
3	9.2	7.2	8.20
4	7.2	5.2	6.20
5	5.2	3.2	4.20

Figure 3: Heating system sizing procedure in optimization model.

As suggested by UNI ENI 10349-2 (UNI, 2016b), in order to size the heating system, the maximum thermal load of the building in stationary conditions, considering the outdoor temperature equal to the minimum winter temperature for the chosen location (-5°C), is assessed. For the starting reference building, the heat pump is sized to cover the whole heating thermal load at the external design condition (A-2W55 with a COP of 1.8). Then, by varying the building insulation level, a decrease of the maximum thermal load is obtained and 5 different commercial heat pump sizes were chosen for all the possible renovation configurations, as specified in Table 2. This assumption was necessary in order to automate the optimization calculations. Furthermore a small water tank is introduced in the heating system to limit the on-off cycles of the heat pump. The water supply to the heating system is regulated by means of a compensation curve and the design temperature difference between inlet and outlet water is about 10°C .

Figure 3 shows a schematic of the heating system size procedure during the optimization.

Result and discussion

In order to evaluate the impact of the different buildings refurbishment strategies on the energy flexibility, the FPI is calculated firstly for the starting building and then for each energy requalification intervention. According to the boundary conditions specifications described in the previous section, the representative winter day for Milan is January 27 (average daily temperature 3.6°C).

The FPI for the starting building shows very poor flexibility performance. Without thermal insulation (as showed in Figure 1, referred to the starting reference building), the comfort limit condition is reached very quickly: the duration of the response period, t_{res} , is about 0.05 hours. For this reason, even if the low thermal inertia of the distribution system allows to restore the initial comfort condition rapidly (t_{rec} about 0.13 hours), the building energy flexibility is almost nothing and the building is labelled in flexibility class D with a FPI of 2.5. For this case, the building thermal energy demand is $27224 \text{ kWh} \cdot \text{year}^{-1}$.

Results show that if the building thermal load decreases by insulating only a singular part of the envelope (external

walls, roof or floor) the flexibility performance does not increase significantly. Looking at Figure 4, where FPI values are calculated by increasing thermal insulation thickness of external walls, it can be observed that even with 11 cm of thermal insulation, the flexibility class remain D. Similar considerations can be made if the thermal insulation is added to the roof or to the floor or if the windows are replaced. This is due to the fact that the t_{res} parameter is always very low (it reaches the maximum value of 0.15 hours with a roof thermal insulation thickness of 14 cm) and the η_{DR} assumes values close to zero. Indeed, for such short times, the effect of the DR event on energy consumption is negligible. With these single renovation strategies indeed, the heat losses of the other not insulated surfaces are still significant and the comfort limit condition is early reached.

Considering the potential economic saving derived from participation to a DR programme during the representative day used for the FPI calculation, Figure 4 shows it in case of increasing insulation of the external walls: the cost saving is always very low (the maximum value is 0.06 €).

Figure 4: Flexibility performance indicator and economic benefit during the DR event by varying the thermal insulation thickness of the external walls.

In Figure 5, instead, it is possible to see the effect on the thermal energy demand of every single refurbishment solution, combined with the economic investment requested to realize it (Eurospottello Veneto, 2019). If a good level of energy saving, combined with low investment cost, is desired, roof insulation seems to be the best solution for a similar one floor single house. Indeed

with 14 cm of thermal insulation to the roof, 35% energy savings are obtained compared to the original building with an investment of about 6000 €.

Figure 5: Single renovation strategy cost and achievable thermal energy demand saving.

Regarding the energy flexibility, no improvements are observed even if two portions of the structure are thermally insulated or if one of them is combined with windows replacement. The flexibility class remains D, if thermal insulation is added to the external walls and roof, while if also the windows are replaced, a slow improvement begins to be observed for high levels of insulation. In particular, the building flexibility class becomes C with an FPI of 4.2 with windows replacement, 11 cm of insulation for the external wall and 14 cm for the roof. In this case, t_{res} increases, but not enough (about 0.70 hour), however the effect of the not-insulated floor prevails on the thermal inertia of the remaining envelope. Introducing a minimum level of thermal insulation (1 cm) in the floor stratigraphy increases sensibly the FPI values. Referring to Figure 6, this behaviour can be observed. The building reaches flexibility class B (FPI= 6) with 12 cm of thermal insulation in the roof and 8 cm in the external walls. The response period is about 2.37 hours, the recovery 0.25 hours and the actual energy variation E_{DR} is about 2.83 kWh_e.

Figure 6: Flexibility performance indicator by varying the insulation thickness in the roof and external walls with windows replacement and a minimum floor insulation (1 cm, fixed).

However, a strong improvement can be observed only if each part of the envelope is well thermally insulated and windows are replaced. Figure 7 shows the building flexibility performance by varying the thickness insulation in the external walls and in the roof, assuming a high level of thermal insulation in the floor (11 cm) and new windows. The thermal loss reduction derived from

the whole envelope insulation, in addition to the effect of more energy efficient windows, allows the increase of building thermal inertia, which can be activated during the DR event so to maintain for long time the internal comfort conditions.

Figure 7: Flexibility performance indicator by varying the insulation thickness in the roof and external walls with windows replaced and 11 cm floor insulation (fixed).

Figure 8: Thermal energy demand reduction by varying the insulation thickness in the roof and external walls with windows replaced and 11 cm floor insulation (fixed).

It is possible to see that the high level of thermal insulation in the floor allows to obtain a strongly increasing trend of the FPI with the increase of the insulation thickness of the other walls of the building.

The maximum FPI achievable is 10.8 (class A2) and the building can maintain for about 9.4 hours (t_{res}) the comfort conditions. Important FPI improvements are anyway observed for high values of thermal insulation (from 8 cm upwards for external walls and roof). Medium insulation thickness (from 5 to 7 cm) allows to obtain FPI values between 4.5 and 7, so buildings are generally classified in flexibility class C or, at maximum, B.

As far as the thermal energy demand is concerned, Figure 8 shows that the energy efficiency improves faster than flexibility with the envelope insulation thickness. Already with medium insulation thicknesses for external wall (5 cm) and roof (7 cm), an energy demand reduction of 73% can be achieved (if also windows are replaced and a minimum level of 1 cm thermal insulation in the floor is added). This percentage becomes 70% if a higher insulation thickness (11 cm) is present in the floor stratigraphy and 80% if the building is realized with the highest insulation level. This trend is counterbalanced by higher investment costs that need to be addressed: about

24300 € is the estimated investment required in the latter case. However, the building, due to its higher energy efficiency, will have its heating costs reduced (of about 83%) and, due to its good energy flexibility characteristics, it will be able to obtain also an economic benefit deriving from participation in DR programs. Figure 9 shows an estimation of the cost savings during the representative day for the DR event used in the FPI calculation. The economic benefit due to DR programme participation follows the results obtained for the energy flexibility with the different renovation configurations. When the building has an energy flexibility class A2, about 1.60 €/day can be saved if the DR programme is activated, without jeopardize the comfort of the users.

Figure 9: DR economic benefit by varying the thermal insulation thickness in the roof and external walls with windows replaced and maximum floor insulation (11 cm, fixed).

However, it is important to note that this economic saving is evaluated assuming the flexibility labelling method boundary conditions. It represents a potential saving, assessed under design conditions (heating system on during all the t_{DR} in the reference case). Lower values can be obtained if the real system operation is considered for the all heating season, because for example the DR events are shorter than the reference one for FPI calculation, especially in colder winter days. Considering a building with the highest level of thermal insulation, comparing the reference operation case (no DR programme participation) with the case of every-day DR event (as the one considered in the flexibility labelling method), a reduction in electricity consumption of 6.1% and a cost saving of about 7% is obtained for the whole heating season.

Conclusion

The objective of this work was the evaluation of different buildings refurbishment strategies on buildings energy demand management ability. Starting from a reference old not insulated building, the energy flexibility improvement due to different energy efficiency interventions is quantified. In particular the insulation thickness of the building envelope (floor, roof, external walls) and the windows features are varied. The heating system size is modified in compliance with the reduction of thermal energy demand and with commercial systems specifications available.

From the results, it is possible to see a consistent reduction of thermal energy demand by increasing the insulation

level of the building envelope. However, the same behaviour is not observed for the energy flexibility. The positive effect on flexibility due to building thermal mass is evident only if the thermal insulation is applied at the same time in the external walls, floor and roof. If there is even only one surface with high heat losses, the building is not able to maintain in an acceptable band the internal comfort and the flexibility performance is low. The adoption of new and efficient windows is also fundamental to achieve good FPI values.

From the economic point of view the same considerations can be made. While the energy cost savings due to energy efficiency maximization are evident for the energy demand reduction, the DR economic benefit is not so obvious. From an analysis at design conditions, high savings in the electricity bill derived from the participation of highly flexible users in DR programs are obtainable (about 1.60 € per day). However, the effect decreases a lot if the normal operation of the systems is considered.

Concluding, an innovative tariff structure should be introduced to exploit the flexibility of building energy demand, since it is highly influenced by the daily operation of the system.

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Nomenclature

AWHP	air water heat pump
COP	heat pump coefficient of performance
DR	demand response
DSM	demand side management
E_{DR}	actual energy variation
EFB	energy flexible building
FPI	flexibility performance indicator
GG	degree days “gradi giorno” in Italian
HVAC	heating, ventilation and air conditioning system
NZEBs	Nearly Zero Energy Buildings
$\dot{P}_{res}^*$	committed power effect dimensionless
$\dot{P}_{DR}$	electricity consumption in DR event case
p_i	dimensionless FPI contribution weight
$\dot{P}_{rated}$	heat pump power design
$\dot{P}_{res}$	committed power effect
PSS	peak shaving strategy
RES	renewable energy sources
SBC	standard boundary conditions
SFH	single family house
SRI	smart reading indicator
T	temperature
t_{rec}^*	recovery time dimensionless
t_{res}^*	response time dimensionless

t_{DR}	DR time
TES	thermal energy storage
TMY	typical meteorological year
t_{rec}	recovery time
t_{res}	response time
U	thermal transmittance
η_{DR}	actual energy variation dimensionless

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