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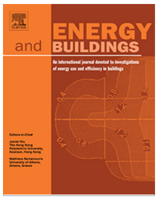

Cost-effective building renovation at district level combining energy efficiency & renewables – Methodology assessment proposed in IEA EBC Annex 75 and a demonstration case study

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ABSTRACT

Building renovation plays a key role in reducing greenhouse gas emissions and achieving the climate protection goals. The district scale approach is one of the most effective approaches to accelerate this process of reducing the energy consumption in the building sector as increasing its renovation rates. In this context, the Energy in Buildings and Communities Programme of the IEA, IEA-EBC started in 2017 the project "Annex 75: Cost-Effective Building renovation at District Level Combining Energy Efficiency and Renewables" aiming to explore optimal opportunities of district renovations from a cost-benefit perspective. IEA Annex 75 is a co-operative effort of participants from 13 different countries: Austria, Belgium, China, Czech Republic, Denmark, Germany, Italy, The Netherlands, Norway, Portugal, Spain, Sweden and Switzerland. In this paper, key elements of the methodology developed in Annex 75 project are presented. This methodology aims to facilitate the identification of optimal solutions in different European countries, enabling to explore similarities and differences amongst them, with a particular focus on the balance between energy efficiency measures and renewable energy measures. After a detailed description of the developed methodology, it is also applied to a case study located in Portugal and results obtained are analysed in detail. The paper demonstrates the usefulness of the methodology for evaluating and identifying optimal solutions in renovations at district scale, as well as for successfully addressing the research questions investigated by the Annex 75 project. They also provide some insights regarding the specific case study, showing that, although district systems are not usual in the current Portuguese context, these centralised solutions in renovations at district level are cost-effective interventions that can lead to significant reductions of greenhouse gas emissions and non-renewable primary energy use.

1. Introduction

It is well known that over 40% of the global energy consumption and 30% of greenhouse gas (GHG) emissions are related to the building sector [1]. Already in 2007, the Intergovernmental Panel on Climate Change synthesis report identified that the building sector was the sector with the main economic mitigation potentials using technologies and practices expected to be available in 2030 (estimated from bottom-up studies) [2]. In this context, the European Union (EU) adopted in 2007 the "2020 Climate and Energy Package" [3], and the roadmap was updated in October 2014 with the definition of the "2030 Climate & Energy Framework" [4]. As far as the building sector is concerned, the Directive 2012/27/EU on Energy Efficiency [5], which aims at increasing the energy efficiency for achieving aforementioned objectives, highlights the potential for saving primary energy (PE) of district heating and cooling systems, and it urges the Member States to carry out a comprehensive assessment of the mentioned potential. Earlier, the recast of the Energy Performance in Buildings Directive (EPBD) [6] involved a turning point on the path towards the improvement of the efficiency of the building stock. This directive

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introduced two important concepts: cost-optimality and nearly Zero Energy Buildings (nZEB), but mainly focused on new buildings. However, taking into consideration the low rates of replacement of the building stock in Europe [7], new buildings clearly can only play a smaller role in the overall reduction of GHG emissions related to the building stock. Hence, the main challenge is linked to the existing building stock, and energy renovation will play a key role on the overall objective of facing climate change by reducing carbon emissions. As a consequence, as mentioned in [8], several cities around the world have established strategic targets for GHG reductions focused on the urban environment, including the building stock amongst the main target areas.

It is within this background that IEA-EBC launched in 2010 the project "Annex 56: Cost-Effective Energy and Carbon Emissions Optimization in Building renovation". This project involved 11 European countries with the aim of developing a methodology to enable cost-effective renovation of existing buildings by identifying the optimal balance point of energy efficiency (EE) and renewable energy supply (RES) measures in a cost/benefit perspective. The project went on until 2017 and it gave rise to several academic publications, which can be found in the literature [8,10-14] and in different reports, which are available on the website of the project [15].

However, building renovation rates have not reached targeted goals for many years [16], and there is a general agreement that it is necessary to accelerate these rates. Therefore, the district scale approach is considered to be as one of the potentially most effective approaches to speed up the process of reducing greenhouse gas emissions in the building sector. Moreover, this approach can also allow taking advantage of the interactions and synergies amongst the different buildings and optimising the implementation and integration of renewable energy sources. To implement this approach, municipalities and other stakeholders need methods and tools that support them to identify the potentials of different building clusters for reducing greenhouse gas emissions and energy consumption as well as the optimal solution in each case [8]. The idea of fostering integrated district-level energy efficiency renovation approaches are also mentioned by the European Union in different Commission recommendations, such as CR-EU 2019/786 of 8 May 2019 on building renovation [17]. This idea is furthermore indicated in the update of the EPBD in 2018, which states that the Commission *"shall review this Directive by 1 January 2026 at the latest"* and *"as part of that review, (...) examine in what manner Member States could apply integrated district or neighbourhood approaches in Union building and energy efficiency policy (...) by means of overall renovation schemes applying to a number of buildings in a spatial context instead of a single building"* [18].

As a consequence, a substantial amount of publications can be found in the literature focused on this field. One example is the already mentioned work published by S. Paiho et al. [8]. S. S. Castro et al proposed in [19] a decision matrix as a tool to identify the most appropriate retrofit measures of an existing building. Another example is the work recently published by V. D'Alonzo et al. [20], where a methodology for the building stock analysis of the residential sector is presented, which integrates input data in a Geographical Information System, without using the "archetypes approach" and simulation tools. Several publications have also focused on more specific issues on this field, such as on evaluating the different available tools for this kind of assessments at district scale. One example is the work presented by S. Ferrari et al. in [21], focused on methods for estimating building energy demand at district level; or [22], which evaluates available tools for assessing energy systems for building clusters.

Based on all these references, the Annex 75 project aims to go further, by means of applying a comprehensive analysis which covers not only the energy, economic and environmental issues, but also additional issues such as identifying opportunities and barriers on the relations between the different involved stakeholders or policies and incentives for boosting energy renovations. To do that, the methodology presented in this paper will be applied to different case studies located in different countries, in such a way that its application will allow to carried out a comparative analysis targeted to identified the optimal strategies and lessons learned which will be able to be extrapolated to any other district according to its specific conditions.

2. IEA-EBC Annex 75. Cost-effective building renovation at district level Combining energy efficiency & Renewables

In the context previously explained, IEA-EBC started in 2017 a new project "Annex 75: Cost-Effective Building renovation at District Level Combining Energy Efficiency and Renewables". The project involves 25 institutions from 13 different countries and, in this case, it explores the opportunities of building renovations from a cost-benefit perspective at district level.

The project aims at assisting in clarifying the cost-effectiveness of various approaches combining both EE and RES implementation and focusing on the optimal combination between them, with respect to various possible starting situations in a specific city district. Thus, in particular the following research questions (RQ) are investigated within the Annex 75 project:

- RQ1. What are cost-effective combinations between RES measures and EE measures to achieve far-reaching reductions in GHG emissions and PE use in urban districts meeting the preset targets?
- RQ2. How do related strategies compare in terms of cost-effectiveness and impacts with strategies that combine a decentralised switching of energy carriers to RES with EE measures on the buildings' envelopes?
- RQ3. Which factors determine the cost-efficient balance between efficiency measures on the buildings envelopes and measures to use RES, if far-reaching reductions in GHG emissions and PE use in urban districts are the targets?
- RQ4. To what extent does the cost-effectiveness of renovation measures on the building envelopes in the case of a local district heating system based on RES differ from the cost-effectiveness of such measures in case of a decentralised use of RES for heating in each individual building?

Given the current necessity to achieve a building stock free of greenhouse gas emissions, it is in particular investigated which approaches, taking into account various possibilities for energy efficiency measures and renewable energy measures, allow to achieve districts supplied entirely with renewable energies at least costs.

For answering these research questions, the project focuses on four specific objectives: i) to give an overview on various technology options, taking into account existing and emerging efficient technologies with potential to be successfully applied within that context; ii) to develop a methodology to be applied to urban districts in order to identify such cost-effective strategies; iii) to illustrate the development of such strategies in selected case studies and gather related best-practice examples; and finally, iv), to give recommendations to policy makers and energy related companies on how they can foster the uptake of cost-effective combinations.

As far as the second objective is concerned, a specific methodology is developed and applied in generic calculations as well as in parametric calculations based on real-world case studies. Through this application, it is intended to identify the factors that affect the cost-effectiveness of renovation strategies for urban districts, as

Table 1
Project approach to different typology-related issues.

Project Approach	
Environment *(Urban – Suburban – Rural)*	Focus on urban and suburban districts, because energy densities are higher than in rural districts, making district-based solutions therefore potentially more attractive
Size of Buildings *(Single family – Multifamily)*	Focus on districts containing multi-family residential buildings, also for reasons of potential attractiveness for district-based solutions
Available options of RES	Focus on districts where a large number of options are available (both in terms of RES as well as possibilities for renovation of building envelopes) to be able to compare several scenarios.
Initial Situation	Focus on districts currently heated mainly by fossil fuels (either through centralised or through decentralised systems).

well as evaluate synergies and trade-offs between RES measures and EE measures, and between individual and collective solutions.

The proposed methodology builds on the methodology developed for individual buildings in Annex 56 [23] extending it to the level of groups of buildings. This change of scale, as well as the objective of applying it in different contexts, involve some issues that should be taken into consideration. On the one hand, this methodology should be flexible enough to be applied to the different specific conditions existing in each country; on the other hand, to clearly define how to make comparisons between different cases and obtain consistent conclusions. The objective of the methodology is to support decision makers in the evaluation of the efficiency, impacts, cost-effectiveness and acceptance of different possible strategies for renovating urban districts, making the identification of the most suitable options easier. The project plans to develop or adapt one or more calculation tools to support the application of the methodology in case-specific assessments.

Hence, the objective of this paper is to describe the mentioned methodology in detail and demonstrate its use by applying it to an example of a case study located in Portugal, in the Picoto neighbourhood, a social housing neighbourhood built in the 90′s and located in Braga region, in the north of Portugal.

The rest of the paper is organised as follows: section 3 gives a detailed description of the proposed methodology, where different assumptions and considerations related to energy as well as economic and environmental issues are presented. Based on mentioned basis, the general procedure for evaluating cost-effective renovation strategies is described in section 4, whereas the methodology is tested and demonstrated on a case-study located in Portugal in section 5. Finally, the main conclusions and remarks are addressed in section 6.

3. Methodology for assessing cost-effective building renovation strategies at district level: scope, system boundaries and framework conditions

In a similar way as defined by S. Paiho et al. in [8], this paper considers a "renovation at district scale" as a refurbishment of different buildings located in a same area and with a sort of relation amongst them, using the term "district" without referring to any juridical or administrative purpose.

Considering this global definition, the Annex 75 focuses mainly on residential districts, composed of both single and multifamily buildings. Districts with other buildings with similar characteristics, such as schools or simple office buildings without complex HVAC systems can be also considered. Complex HVAC systems refers to HVAC systems that are used not only for removing/replacing air in order to achieve a good indoor climate, but also include advanced control systems aimed at optimising the operation for heating and cooling such as, for instance, occupancy-based strategies for operating, or predictive control strategies for temperature control of air handling units. Typically, more complex HVAC systems would also require more detailed modelling, which is outside the scope of the methodology. Even though considering different uses usually drives to a more optimal solution by increasing the synergies amongst the evaluated buildings, it makes the assessment more complex, without providing additional information on the focus of the aforementioned research questions of this project. As far as the size of the district is concerned, there is no limit in the proposed methodology and it will depend on the specific features of the evaluated district;

Finally, regarding the typology of districts, different distinctions could be made according to the environment, size of buildings, available options of RES and initial situation of a given district. The project approach to these issues is summarised in Table 1.

The assessment considers the energy use for space heating, space cooling, domestic hot water (DHW), ventilation, lighting and auxiliary electricity consumption for building integrated technical systems (fans, pumps, electric valves, etc.). Additionally, it is recommended to include electricity for appliances, as they contribute to electricity consumption and internal heat gains. Besides, it will also make it more feasible to evaluate the potential of onsite generation (e.g. photovoltaic systems) to cover these loads.

3.1. Definition of key performance indicators

Once the scope has been defined, the main indicators for evaluating and comparing different districts amongst them are selected. These indicators allow to assess the level of sustainability and cost-effectiveness of a given renovation project, or comparing different projects between them, as well as they are a useful instrument to help to check to what extent the project goals are achieved. Several references related to key performance indicators (KPIs) could be found in literature. It is interesting, as a way of example, the review on KPIs approach in building renovation, presented in 2016 by A. Kylili et al. [24], where the authors classified the KPIs found in literature into different categories. After a detailed analysis of the different KPIs included in each category, three indicators have been considered to be most essential and accordingly used in this methodology: GHG emissions (CO_2 eq./m^2.year), PE use (kWh/m^2.year) and annualised total costs (€/m^2.year). Depending on the specific features of each case study, additional KPIs may be calculated, such as energy demand for the different uses (heating/cooling, DHW and electricity), the ratio between RES and total energy needs or the share of electricity supply from the grid in relation to the total electricity consumption of the given case study, to name but a few..

3.2. Energy demand side and energy supply side

The level of sustainability and cost-effectiveness of renovation projects is defined according to the evaluation of these KPIs for each scenario assessed. The assessment is carried out based on matching energy needs of the district with energy supply, as Fig. 1 illustrates. The figure also includes the three indicators selected as essential in this project (in green-lined boxes with

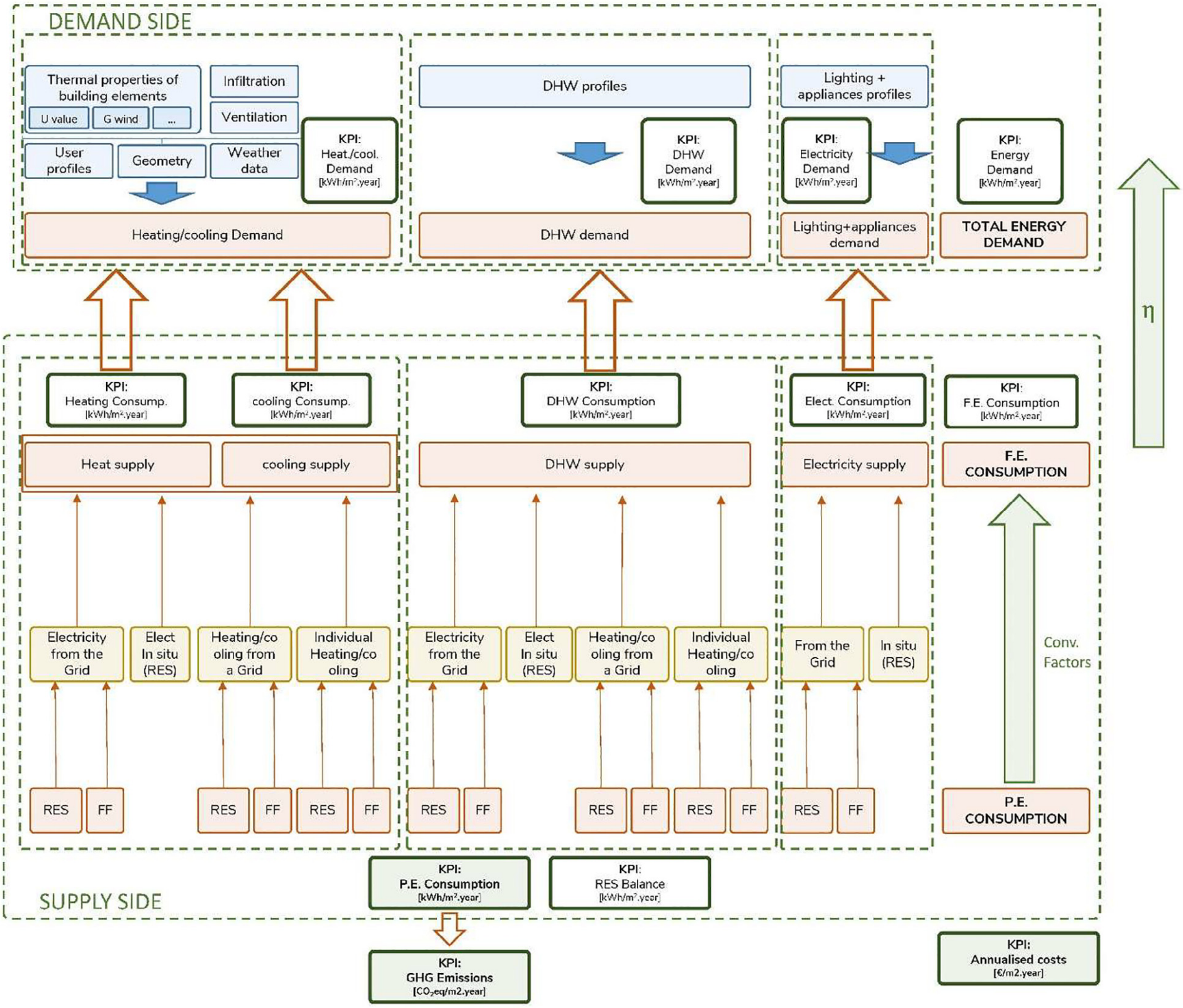

Fig. 1. Overview of principle of matching energy demand side and energy supply side.

green background), as well as other additional indicators that could be useful in the evaluation of different cases (in green-lined boxes with white background). It should be noted that, in districts, buildings usually have different initial situations regarding their thermal envelope, systems, etc. Furthermore, there is the challenge that renovation cycles of the envelopes in a district are usually not synchronised. It is recommended to take such differences into consideration when providing recommendations on how to renovate a given district, as some buildings may be in need of renovation where others may have just had a renovation.

Based on this approach, building clusters can be evaluated using dynamic simulations (they are recommended with an hourly time step), in order to evaluate or specific tools for evaluating the global performance of the whole systems, or considering the demand side on the one hand, and the supply side on the other hand.

The energy needs for heating and cooling of each building of the evaluated district are calculated based on building dimensions and thermal properties. DHW demand, as well as electricity demand, are considered according to standard profiles of the country where the assessed case study is located.

As far as supply side is concerned, both centralised and decentralised energy systems can be taken into consideration in this methodology. Specific interactions amongst the different technologies (e.g. those related to thermal storage) can be considered in detail. Otherwise, simplified methods can be applied, considering general parameters, such as seasonal performance.

When characterising energy systems, four parameters are taken into account: cost (as a function of capacity), service lifetime, conversion efficiency and associated energy carrier. Several similarities with the assessment carried out for individual buildings in the Annex 56 project can be found in this methodology. However, it should be taken into consideration that, in order to extend the assessment to district heating systems, the cost structure of the district heating system should be considered by the different elements in it, in such a way that adding up the costs of all these elements (heating substations, pipes and distribution system or circulating pumps, amongst others) lead to the total costs of the heating system. These costs associated to the different elements include not only investment and maintenance costs (e.g. costs of distribution system include all the necessary work for putting the pipes into the ground) but also the energy losses and inefficiencies through these systems.

Finally, it should be mentioned that there are other parameters, which can play an important role when assessing the cost-effectiveness of district systems, such as the temperature gap between supply and return temperature, diameter of pipes, insulation level of distribution system, or similar specific parameters. However, there is not a specific focus on optimising these parameters for creating optimal systems. The focus is rather on parameters which are directly associated with the optimal balance between EE and RES measures.

Energy use for the different uses is evaluated based on energy needs calculated following the norm EN ISO 52016–1:2017 [25]. Measured energy consumption of a given building or building cluster, if available, can be used to assess the plausibility of the calculated energy needs, but it will not be used as a basis for the assessments. Related GHG emissions and PE consumption are calculated based on these energy values by applying the corresponding emission factors and PE factors of each country.

The GHG emission and PE factors are considered to be annual factors and constant over time. The factors for electricity are supposed to refer to a future country mix based on renewable energy. In addition, in some specific scenarios, it is possible to take into consideration other types of electricity mixes more closely to the current electricity mix.

3.3. Economic analysis

As far as economic assessment is concerned, the previous experience of Annex 56 project is taken as a reference, and a life-cycle approach is chosen to evaluate costs of different renovation opportunities. It includes, in accordance with the guidelines to the EPBD [27]: i) initial investment cost or replacement costs; ii) energy costs (including existing energy and CO_2 taxes); and iii) maintenance and operational costs. These life cycle cost calculations are carried out dynamically. Therefore, it is proposed to use the annuity method for transforming any costs into annual costs, assuming the initial costs, the interest rate and the typical service lifespan for the renovation measures considered. In any case, alternatively, also the global cost method can be used. All these costs are categorised in Fig. 2.

The cost assessment is carried out from a private perspective, i.e. the district is assessed as a unit, with the aim of meeting the main target of the project (i.e. evaluating what type of combinations between EE and RES measures are most cost-effective while satisfying the boundary conditions). Nevertheless, it is considered to be appropriate for the project targets to investigate potential barriers for implementing the most cost-effective solutions satisfying the boundary conditions, due to the fact that several energy actors are usually involved.

As far as taxes are concerned, they are taken into account as given by the national framework conditions for each case study. For CO_2 taxes, it is recommended to investigate various scenarios in a sensitivity analysis when new or a change of related taxes are under discussions in the respective countries.

Subsidies for energy related measures are excluded from the general assessment of costs, in order to make an assessment of the results that identifies optimal solutions regardless the effect of subsidies, which can vary along the time or even depending on the city where the district is located. When investigating the situation of a specific investor, they may nevertheless be included in a second alternative and specific assessment. External costs, benefits and co-benefits are not included. Other issues, such as the effect of the economy of scale are also considered in the methodology.

3.3.1. Energy related costs

Based on the previously defined hypotheses and considerations, the overview of the energy related money flows are presented in Fig. 3. This approach aims at defining in a more detailed way mainly the running costs previously mentioned in Fig. 2 and the links between energy and money flows in a given building cluster.

As depicted, the approach considers the two different types of supply that can be found in any building or building cluster: thermal energy (including heating, DHW and/or cooling) and electricity. Besides, electricity supply can be divided into two different subsystems: electricity supplied from the grid, and electricity produced in situ, by means of renewable energy.

When analysing the energy inputs in the “thermal system”, they can be renewable energy, fossil fuels and auxiliary energy. The output is the energy for the heating, cooling and/or DHW supplies. In both cases, this output comprises useful energy plus distribution losses. Thus, energy inputs equal energy outputs, including the energy losses due to the system inefficiencies. In a similar way, the running costs of a specific system will be those related to the energy purchase ($€_1$ and $€_2$) and costs related to maintenance, management and operation of the system ($€_3$). The sum of these costs directly affects the total operation costs for the system associated with the thermal subsystem ($€_4$).

Regarding electricity from the grid, only final electricity costs are taken into consideration ($€_5$). This cost is in fact the result of the different costs that this subsystem has to cover, such as the energy cost that have to be paid to generators or maintenance cost to the grid, which are out of the scope of this project.

Finally, in the other subsystem considered, “in situ electricity generation from RES”, only energy outputs are considered: energy used in the evaluated district, and energy exported to the grid. As

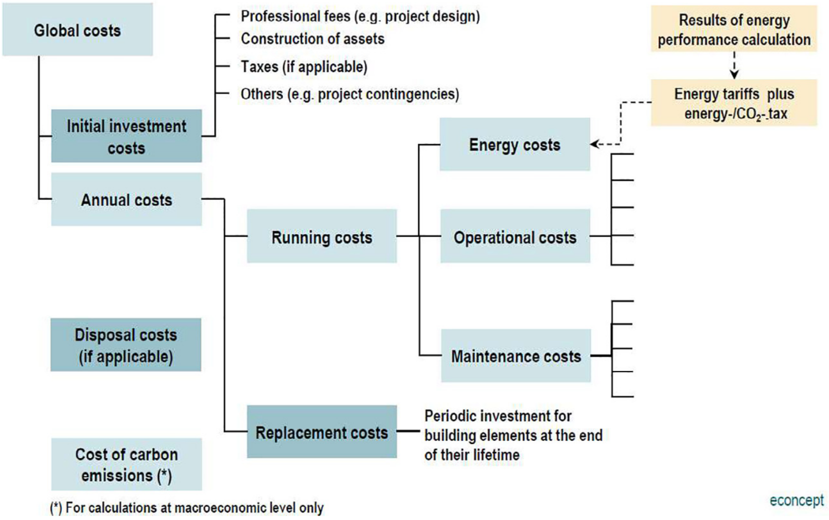

Fig. 2. Cost categorisation according to the framework methodology of EPBD recast [27] (figure from W. Ott et al. in [23]).

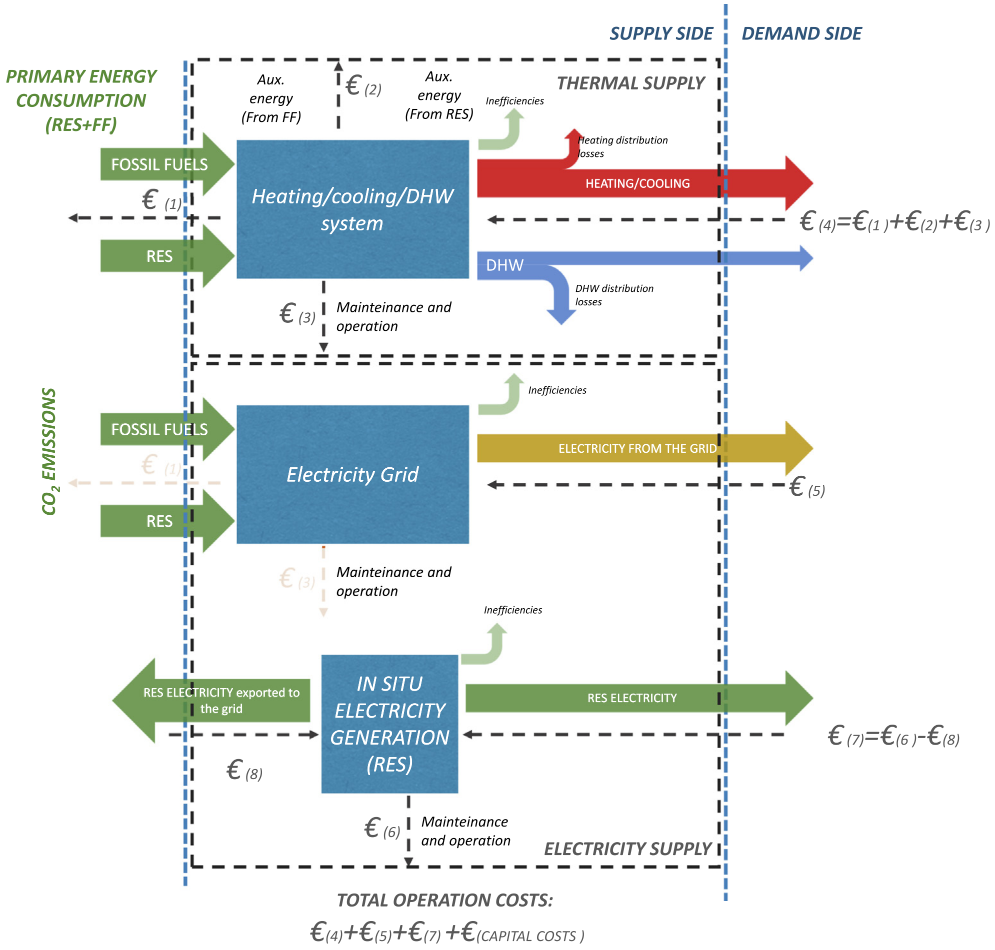

Fig. 3. Overview of money flows related to energy costs and maintenance/operational costs.

far as money flows are concerned, a cost of maintenance and operation (€$_6$) and a benefit of electricity sold to the grid (€$_8$) are considered. The benefit or the deficit of this subsystem for end users is the difference between these two costs (€$_7$). It should be noted that this balance is highly dependent on regulations in each country: even though still in some cases the user has to pay to get rid of electricity production, the majority of the national regulations in European countries are being adapted to facilitate the exports of the electricity surpluses to the grid. However, the terms of these exports (mainly related to the costs) may significantly vary in each country. In addition, there are costs associated with the investments for these systems and resulting capital costs. Besides, it will require to perform hourly calculations if a detailed assessment of this issue is wanted.

Total energy costs and maintenance/operational costs for a related measure or set of related measures are the sum of €$_4$, €$_5$ and €$_7$. In addition, there are costs associated with the amortization of the initial investments for these systems and resulting capital costs (€$_{\text{CAPITAL-COSTS}}$).

3.3.2. Energy prices

As far as energy prices are concerned, it is recommended in this methodology to take into account the expected future increases, in conformity with the report prepared for the European Union in 2016 on energy, transport and GHG emissions trends to 2050 [28]. For that reason, it is proposed to carry out the assessment with energy prices expected for 2030 to take into account future price increases. Further scenarios for energy prices may be included as a part of sensitivity calculations. Regarding the interest rate, an indicative value of 3% is applied, unless more country-specific information is available.

3.4. System boundaries

The system boundary is set to correspond to "net delivered energy". A graphic overview of it is depicted in Fig. 4. Energy carriers delivered to the building are added up, and for on-site generated electricity or heat exported from the building to the grid, a benefit is granted, which improves energy performance and lowers the GHG emissions of the buildings. However, it is proposed to assume that electricity in the grid is based on renewable energy, to take into account upcoming changes in the electricity mix, which then does not lead to any significant benefit other than potentially cost savings.

On-site generation of electricity is taken into account when it is produced from renewable sources. It is distinguished how much of electricity produced is consumed locally, and how much is exported to the grid. Revenues from exports of electricity or heat to the grid or an energy distribution system are taken into account (already considered in Fig. 3, as €$_8$).

4. Assessment procedure

At the beginning of the assessment, the group of buildings to be investigated is defined. This can either be a generic district based

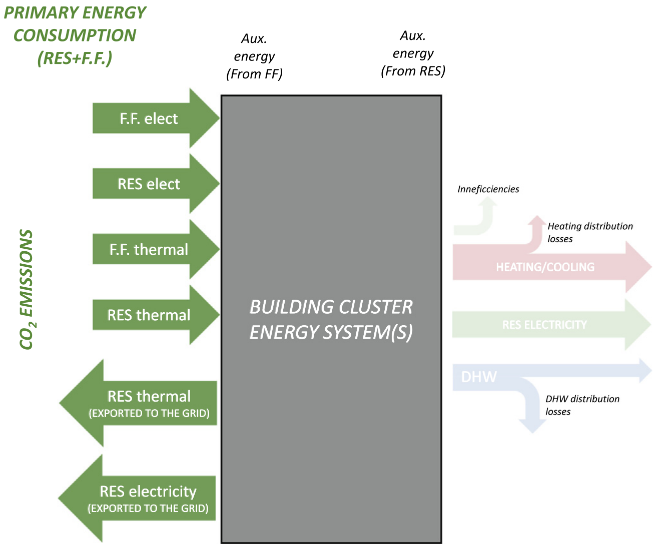

Fig. 4. Overview system boundaries and energy exchanges (RES – Renewable Energy Sources; FF – Fossil Fuels).

on reference buildings (as demonstrated later in this paper), or a specific district of a case study.

As far as thermal features are concerned, one way to estimate the U-values of buildings is by applying top-down approaches involving GIS data information such as a classification of each building according to its building period and latest renovation, and to apply then standard values for these buildings corresponding to their building period or the time of their latest renovation. Other possibilities could be remote-detected energy consumption or estimates made based on measured energy consumption, for example with data from the energy company, or even data provided by energy performance certificates.

4.1. Definition and assessment of reference case

For assessing cost and economic efficiency of energy renovation measures, the procedure developed in the Annex 56 at building scale is taken as a basis [23] and adapted to the district level. Before assessing energy renovation measures, a reference situation is defined to properly determine the effects of energy related renovation on energy use, greenhouse gas emissions and costs by comparing the impacts of the energy-related renovation scenarios with the impacts in the reference case. In Annex 56, to do that, a reference case was defined based on an intervention that comprises renovation measures that would have to be carried out anyway, just to restore the building's functionality (e.g. repainting the walls or repairing the roof to make it again water-proof). It is assumed that these anyway measures do not increase the energy performance of the building, but they involve costs. If necessary, hypothetical assumptions are made about the costs for such measures.

For heating and cooling systems, a replacement is also taken into account in the reference case. This is necessary to assess the costs of installing a new system in comparison with a correct reference scenario. In the reference case, the replacement is considered to be of the same type as the system installed before. Modern heating or cooling systems, even if based on fossil fuels, usually have slightly higher conversion efficiencies than previous systems of the same type. An increase in energy efficiency with respect to the system is usually taken into account also in the reference case. This reference case was designated as "anyway renovation" [23] and it is also applied in this methodology.

The methodology is open to evaluate additional reference scenarios without anyway measures (e.g. in a sensitivity analysis at the end), in order to assess the impact of taking or not into account such anyway measures. It might be argued that assessments without anyway measures for some buildings may be adequate in districts with large differences in renovation cycles of the buildings, as in such district it would be possible that energy renovation measures are carried out in connection with a district-wide renovation on those buildings for which the necessary anyway measures are still far in the future. This point may be taken into consideration in cases studies applying the methodology. However, it is assumed that differences in renovation cycles similarly affects anyway measures and energy efficiency measures in the districts, and it is adequate to take into account in the reference case anyway measures in order to specifically assess the impacts on the costs of energy-related parts of the measures.

4.2. Definition of building renovation scenarios

Once the KPIs of the reference case has been calculated, a set of building renovation measures is chosen, which are taken into consideration for inclusion in building renovation scenarios. Based on this set of renovation measures, either a limited number of combinations of renovation measures are identified as renovation packages for which the assessment is carried out, or an optimisation is carried out to identify the optimal solutions by choosing appropriate combinations through an optimisation engine. With the optimisation, the least cost combinations are sought satisfying the boundary conditions. For the investigated renovation packages, costs and effects of renovation measures are determined.

In this manner, for each building in the district, about 10 renovation packages are investigated, which have progressively higher ambition levels related to the resulting energy performance of the building envelope (by means of energy saving measures) and energy supply systems. A replacement of the heating system is assumed in all cases, whereas heat distribution system including the radiators is assumed to remain the same, even though they can be changed as well.

The renovation packages investigated will be chosen in a way to allow answering the research questions. In order to do this, it is important that varying levels of energy efficiency of the building envelope are investigated, in combination with various types of heating systems. At the same time, it may be useful to align various renovation packages investigated with a variety of standards as occurring in a given country, to make the results more easily interpretable. Evaluating also combinations with at least one fossil fuel based system (centralised or decentralised according to the starting point of the district) and with both a centralised and a decentralised RES systems is recommended.

The size of the heating system is calculated by determining the required peak capacity to maintain the target indoor temperature despite heat losses during wintertime, and it is necessary to take into account that new heating systems can be downsized due to better insulation.

To identify the optimal solution, different approaches can be applied. Here it is proposed to consider as suitable solutions only combinations that result in an energy use covered fully by renewable energies; this includes electricity use, with a combination of electricity produced on-site and electricity imported from the grid. With this condition, the remaining GHG emissions are those associated with embodied emissions of the renovation measures and upstream emissions of the energy carriers. Among solutions that satisfy this condition, the optimal solution is then chosen by taking into account PE use as well as costs.

As mentioned in the previous section, the assessment is based on calculations and not on actually observed energy performance. In reality, it is sometimes observed that the energy efficiency performance levels do not reach the target values according to the calculations. Such observations are referred to as performance gap, which has been profusely studied and several references can be found in the literature, such as the comprehensive work recently published by E. Cuerda et al. in [29]. For carrying out the assessment, it is not necessary to take into account these effects, but it needs to be kept in mind, though, that this may potentially overestimate to a certain degree the cost-effectiveness of renovation measures.

4.3. Expected results and sensitivity analysis

For carrying out the assessments, the main KPIs introduced in section 3.1 are calculated. Thus, in order to assess the cost-effectiveness of different renovation packages, a comparison is made between the reference case and the renovation packages. Results are illustrated evaluating specific GHG emissions vs. costs and specific PE use vs. costs.

Moreover, it is recommended to evaluate the results by varying certain parameters to identify factors that strongly influence the results of the calculations. It may be particularly appropriate to take into account the parameters with higher uncertainties, such as the future development of energy cost, and various parameters characterising the district.

4.4. Relation between energy efficiency measures and implementation of renewable energy systems

Finally, there are several relationships between EE measures and RES measures, which affect significantly the project outcomes and, in consequence, they should be taken into consideration when the assessments are carried out.

The first is the relation between energy consumption and level of insulation of the building envelope. The better insulated the buildings are, the lower are their energy needs and the resulting energy consumption. This effect is stronger on reducing costs in case of fossil fuel based heating systems in comparison with renewable energy based heating systems, due to the lower operational energy costs of the latter.

The second is the importance of modelling the costs of the heating systems in an appropriate way as a function of the capacity of the heating system. This capacity is directly affected by the EE measures carried out, and this relationship is a key factor for assessing synergies or trade-offs between EE and RES measures. Due to economies of scale, the costs for a heating system are usually a logarithmic function of the installed capacity for large capacities. In order to facilitate the assessment, it is proposed to approximate the cost function with a piece-wise linear approximation based on a limited set of discrete capacity/costs relationships.

Finally, a remark related to heat pumps should be done. For them, there is an important synergy with EE measures on the building envelope, because the lower the energy need of a building is, the lower can be (to some extent) the temperature of the heat distribution system, which involves an increase of the efficiency of heat pumps. At the same time, in the case of high efficient buildings, the average outdoor temperature during which the heating system is in operation is lower than for less insulated buildings. As a consequence, the conversion efficiency of heat pumps tends to decrease in more energy efficient buildings. In addition, an increased energy performance of the buildings may have an impact on reducing heat losses in a district heating system. Therefore, it is necessary to take into account these issues when the conversion efficiencies of heat pumps are calculated, as a function of the heat need of the building cluster.

5. Demonstration of the proposed methodology: A Portuguese case study

In order to demonstrate the methodology, parametric calculations were carried on the Picoto neighbourhood in Braga region, located in the north of Portugal (see Fig. 5). Picoto is a social housing neighbourhood built in the 1990′s. In Portugal, most social housing neighbourhoods arose after 1986 to meet the needs of adequate housing conditions of low-income households. In 1993, with the PER (Special Resettlement Program), social housing was significantly promoted, and cooperative housing and municipal

Fig. 5. Case study district. Aerial and general views of the neighbourhood.

Table 2
Specific heating, cooling and DHW needs assumed for the district (Total conditioned area: 1,767 m^2).

	HEATING		COOLING	DHW
	(kWh/m^2 year)	*(kWh/year)*	*(kWh/m^2.year)*	*(kWh/m^2.year)*
District load	164.31	290,335	7.33	26.16

housing emerged. Social housing buildings in Portugal represent about 2% of the total housing stock [30]. Municipalities, small municipal companies or the Institute of Housing and Urban Rehabilitation (IHRU, acronym of "Instituto da Habitação e da Reabilitação Urbana") manage these neighbourhoods. In the majority of these neighbourhoods, affordability and reduced cost of construction were prioritised over quality and energy efficiency criteria. Consequently, indoor thermal comfort conditions are commonly not adequate and significant building pathologies are normally reported in this type of buildings.

5.1. Case study: Picoto social housing neighbourhood

The Picoto neighbourhood is located in Braga, location classified as Csb (Mediterranean warm/cool summer climates) in the Köppen and Geiger climate system [31]. The average annual temperature is 14.2 °C, with the hottest month being July (average of 20.3 °C) and January being the coldest with an average of 8.4 °C [32]. The Picoto social housing neighbourhood is representative of the social housing context in Portugal in terms of the low quality in construction, poor energy performance and inadequate thermal comfort conditions. The neighbourhood is composed of 50 single-family buildings with two floors, organised in seven different blocks with two predominant orientations – North/South and East/West – and with a total heated area of 1770 m^2. In terms of constructive characteristics, buildings in the neighbourhood all have similar building envelopes. There are two types of façades in each building. The façade type 1 (F1) is composed of two layers of hollow bricks (9 cm + 9 cm) and no insulation (U-value of 1.1 W/m^{2}K). The bottom part of the buildings is constituted by the façade type 2 (F2), which is composed of concrete blocks with a U-value of 1.9 W/m^{2}K. The sloping roof is constituted by asbestos cement undulating panels (U-Value of 3.8 W/m^{2}K) and windows are single glazing with an aluminium frame with a U-value of 5.70 W/m^2 K. Individual electric heaters provide space heating and a gas boiler in each building supplies DHW, which are the most common solutions found in this social context. Three general views of the neighbourhood are depicted in Fig. 5. The chosen neighbourhood is not intended to represent the Portuguese building stock, which is marked by a significant heterogeneity. However, some of these characteristics for this group of buildings are very particular of the Portuguese context (where there is no practice of district heating), and it represents a suitable and challenging example for the application of the methodology.

Considering all aforementioned features, the energy demand of the reference case was calculated by means of dynamic simulations carried out with Energy Plus Software. It is recognised here that this type of calculation can be influenced by different sources of uncertainties, being one of the most important, the influence of user behaviour. For these energy calculations, a typical user behaviour and occupancy pattern were considered [33]. DHW load was estimated according to standard values stated in thermal regulations [34]. These values are summarised in Table 2.

Table 3
Main features of the evaluated packages.

Renovation packages for improving the buildings' envelope			
	Façade	**Roof**	**Windows**
P1	ETICS MW 80 mm (F1* and F2**)	Sandwich panel PUR 30 mm	PVC frame with double low emissivity glazing (U = 1.40 W/(m2K)) with solar protection (g = 0.20)
P2	ETICS EPS 80 mm (F1* and F2**)	Sandwich Panel MW 30 mm	Aluminium frame with double glazing (U = 3.30 W/(m^{2}K) and g = 0.76)
P3	ETICS EPS 80 mm (F1* and F2**)	Sandwich panel PUR 30 mm	Aluminium frame with double glazing (U = 3.30 W/(m^{2}K) and g = 0.76)
P4	ETICS EPS 80 (F1*) ETICS EPS 120 (F2**)	Sandwich Panel MW 100 mm	Aluminium frame with double glazing (U = 3.30 W/(m^{2}K) and g = 0.76)
P5	ETICS MW 160 mm (F1*) ETICS MW 200 mm (F2**)	Sandwich Panel MW 100 mm	PVC frame with double low emissivity glazing (U = 1.40 W/(m^{2}K)) with solar protection (g = 0.20)

ETICS – External Thermal Insulation Composite System; MW – Mineral Wool; EPS – Expanded Polystyrene; PUR – Polyurethane foam; PVC – Polyvinyl chloride; *F1 – Façade Type 1; **F2 – Façade Type 2

5.2. Renovation scenarios

In order to study the effects of the renovation interventions on the neighbourhood and to test the research questions under study in the project, five packages of building envelope measures (Table 3), as well as five system solutions were analysed (listed in Table 4). Simulations were performed by means of numerical simulations, using Energy Plus, a dynamic energy simulation software [35]. The simulated interventions are focused on the neighbourhood scale and, therefore, the packages of renovation measures were considered to be implemented in every building in the neighbourhood. The chosen renovation measures in the packages were aggregated after a preliminary individual assessment and represent common practices in Portugal and in this social housing context. In addition, when pertinent, the materials used in interventions on façades type 1 (F1) and type 2 (F2) were distinguished and are indicated in Table 3. Systems were designed using a centralised approach (i.e. one system for the whole neighbourhood), except for the conventional decentralised system solution (electric heater for heating, multi-split system for cooling and gas heater for DHW), which represents the individual default system normally considered in residential calculations [34] and was considered useful for comparison purposes. Centralised simulated systems were designed to meet 100% of the heating, cooling and DHW needs, with exception for the centralised biomass boiler with condensing technology (ESS 1), which does not consider cooling. This approach is considered possible in the Portuguese thermal regulation [34], whenever the overheating risk in summer is minimum, which is quite common in a substantial part of the Portuguese territory. There are three simulated energy supply systems based on heat pump technology (ESS 2, 3 and 4). Energy supply systems 3 and 4 also considered other sources of renewable energy supply. The heat pump + solar thermal (ESS3) considers that DHW energy needs are offset by the implementation of solar thermal panels. This option reflects a practice commonly adopted in Portugal. Motivated by current national thermal regulations and subsidies, by the availability of yearly solar radiation and affordable investment costs (1.45€/kWh.a), the use of solar thermal panels for offsetting DHW is a generalised approach for reducing

Table 4
System solutions.

Energy supply system (ESS)	Heating	Cooling	DHW	RES
1: Conventional Decentralised	Electric Heater h=1	Multi-split EER=3	Natural Gas Heater h =0.71	-
2: Centralised Heat Pump	Heat Pump COP/SCOP=4.06/3.77	Heat Pump EER/SEER=3.97/8.41	Heat Pump COP=4.10	-
3: Centralised Heat Pump +ST	Heat Pump COP/SCOP=4.06/3.77	Heat Pump EER/SEER=3.97/8.41	Heat Pump COP=4.10	ST (DHW)
4: Centralised Heat Pump +PV	Heat Pump COP/SCOP=4.06/3.77	Heat Pump EER/SEER=3.97/8.41	Heat Pump COP=4.10	PV (zero)
5: Centralised Biomass Boiler	Biomass Boiler h=1.07	(zero)	Biomass Boiler h=1.07	-

ST – Solar Thermal; PV – Photovoltaic system.

energy demand in residential buildings. For this approach, it would be required about 150 m^2 of available area. The heat pump + photovoltaic energy supply system (ESS4) assumes that the heating, cooling and DHW energy needs are is supplied by crystalline silicon photovoltaic panels supported by battery storage. This approach assumes no restrictions on the availability of physical space for its implementation and intends to understand whether centralised PV systems can be a cost-effective alternative for the decarbonisation of the neighbourhood. The investment costs of PV panels are higher than in the case of solar thermal panels (2,07€/kWh.a) and, according to calculations, implementation of PV panels to offset the total primary energy needs would require, in this case, 670 m^2 of available area.

Regarding the economic assessment, the investment cost for the different renovation packages, as well as for the different energy supply systems (including grid and system implementation costs) were collected from market-based suppliers and from an established costs database widely used in the construction sector in Portugal [36]. Similarly, energy costs assumed in the analysis are 0.21 €/kWh for electricity, 0.06 €/kWh for natural gas [37]. Regarding the evolution of energy costs, and to reduce uncertainty, the analysis took into account results from established studies [38,39]. An interest rate of 5% was considered in this analysis. For comparison reasons, in the cost-effectiveness calculations, the reference case considers that an “anyway renovation” (i.e. an intervention for maintenance reasons, not improving the energy performance of the buildings) was performed.

5.3. Results from the parametric studies

The main results from parametric studies are presented in Fig. 6, in terms of emissions per year (kgCO$_2$eq/(m^2.year) and Non-Renewable Primary Energy (NRPE) (kWh/(m^2.year), per annualised costs. Results show that the lowest annualised costs are achieved when the ESS 2 presented in Table 4 (centralised heat pump) is used. Specifically, annualised costs range in this case from 47.60 to 62.05 €/m^2, depending on the energy saving measures implemented on the envelope. When the NRPE and emissions are the focus, ESS 4 and ESS 5 (Centralised heat pump + PV and Centralised Biomass Boiler, respectively, as presented in Table 4) present the best performance achieving, in both cases, a zero emission district, regardless of the renovation package implemented on the envelope. Interestingly, these combinations achieve this performance with very different ratios of RES for the total energy needs. For the packages being combined with ESS4 this ratio ranges from 0.41 to 0.47, depending on the package of measures for improving the building envelope. However, when ESS5 is considered, every package presents a ratio of 1.

Regarding the renovation packages proposed in Table 3, it could be observed that P5 (ETICS MW 160 mm + ETICS MW 200 mm + Sandwich Panel MW 100 mm + PVC frame with double low emissivity glazing) is the package of renovation measures that consistently leads to higher reductions of NRPE (an average reduction of 375 kWh/m^2.year in all EESs), although at a considerable higher cost when compared to the rest of the packages. Despite this, there are differences in the hierarchy of measures depending on the energy supply system. For the EES1 (Conventional Decentralised), the ESS4 (Centralised Heat Pump + PV) and EES5 (Centralised Biomass Boiler), the cost optimal measure is P3 (ETICS EPS 80 mm + Sandwich Panel PUR 30 mm + double glazing aluminium windows), with annualised costs of 80.02 €/m^2, 67.14 €/m^2 and 57.30 €/m^2, respectively. However, for EES2 (Centralised Heat Pump) and ESS3 (Centralised Heat Pump + ST) is P2 (ETICS EPS 80 mm + Sandwich Panel MW 30 mm + double glazing aluminium windows), with annualised costs of 47.60 €/m^2 and 56.45 €/m^2.

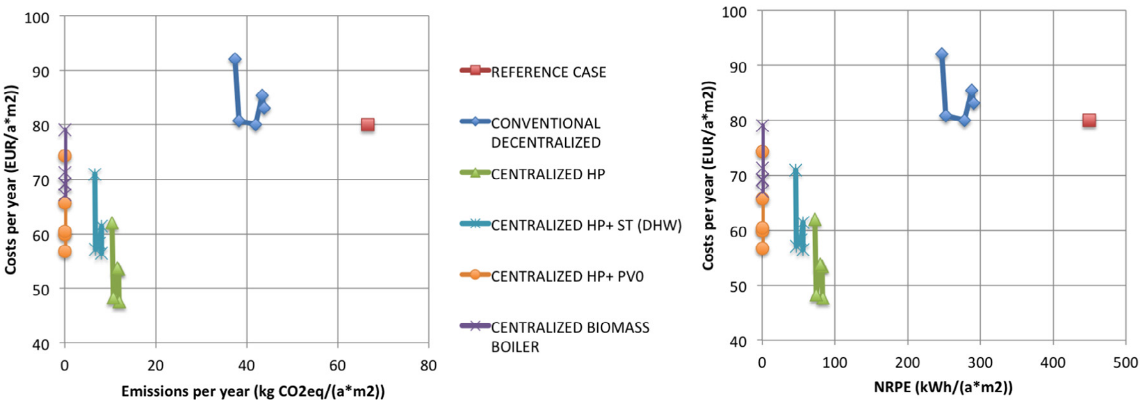

Fig. 6. Calculation results from Picoto neighbourhood simulations.

Results indicate that all the analysed centralised approaches are cost-effective. It is worth highlighting that besides the investment in systems and building envelope measures, the initial costs also include the cost of distribution (e.g. piping and associated civil works). In fact, the results from every renovation measure, when combined with the decentralised systems, present significantly higher global costs than the reference case. In opposition, the renovation package P2 (ETICS EPS 80 mm + Sandwich Panel MW 30 mm + double glazing aluminium windows) using a centralised Heat Pump is the cost-optimal intervention for the Picoto neighbourhood. Relevantly, it should also be highlighted that renovation measures simulated in combination with ESS4 (Centralised Heat Pump + Photovoltaic) and ESS5 (Centralised Biomass Boiler) can lead the Picoto neighbourhood to an energy and carbon emissions neutrality, while maintaining cost-effectiveness. This result is significant in the light of the initial costs being recurrently identified as one of the main barriers for implementation of the energy renovation interventions. Due to the size of the required systems and their high initial investment costs, this issue can represent a major hurdle. In these calculations, costs just for the centralised heat pump system represent a 50% increase in relation to the cost of all the necessary individual electric heaters considered in the decentralised approach. However, the consideration of a lifecycle perceptive of the costs, allows for a deeper understanding of the lasting effects and the advantages potentially drawn from such an intervention.

In addition, both ESS4 and ESS5 (as well as Heat Pump Centralised + Solar Thermal) surpass the minimum requirements (both in terms of energy efficiency and renewable energy supply) for nZEB (nearly zero energy buildings), which will be mandatory for new buildings from the 1st of January of 2021. In Portugal, the minimum requirements that a residential building must meet in order to reach the nZEB level are to have primary energy needs 50% lower than a predefined reference level and renewable energy sources supply at least 50% of the annual primary energy needs [40].

Even though the research questions evaluated in the Annex 75 project should be addressed once considering different case studies evaluated across Europe and under different conditions, some insights related to the mentioned research questions could be identified looking at these results. This way, it is demonstrated how the proposed methodology could lead to find the answers when applying it in different case studies. In this case study, results suggest that cost-effective combinations between RES and EE measures are achievable using centralised approaches. In response to RQ1, it is relevant that the balance between the application of a centralised Heat Pump and Photovoltaic panels in combination with a package of renovation measures on the envelope (even the ones not necessarily addressing the full potential of energy savings from the building envelope, such as P3, for example) can lead the district to zero energy and carbon emissions neutrality within the limits of cost-effectiveness. On the other hand, as a response to RQ2, there is a greater difficulty, at this scale, in achieving balance in combinations regarding cost-effectiveness in a decentralised approach, like ESS1. In fact, results from this analysis show that only one package of renovation measures (P3) allows for cost-effectiveness in the decentralised approach to the neighbourhood. Moreover, and in relation to RQ3, results suggest that the efficiency of the energy supply system (which leads to significant operational energy savings during the building lifecycle) can be a key factor for the cost-effectiveness of the balance between energy efficiency measures and renewable energy supply. Additional factors arising from this analysis, with particular relevance to the Portuguese context, and influencing the balance of combinations are related to the pre-existing situation of the buildings in the neighbourhood (namely in terms of low energy performance) with the available area for implementation of RES and its cost/efficiency ratio, as well as with the need for an additional cost in storage solutions. This is particularly important in the comparison between solar thermal and PV panels, for example. Solar thermal (if used for DHW) allows easy and inexpensive storage while the cost of storing electricity produced by PV panels is not negligible.

6. Conclusions and future works

Evaluating cost-effective strategies for reducing GHG emissions and energy use in buildings in cities at district level is a complex task. There are different research questions that can be investigated in this context. The methodology proposed by the Annex 75 project and presented in this paper provides a basis for investigating particularly the cost-effective balance between carrying out energy efficiency measures and deploying RES measures in the renovation of buildings at district level, and its application has been demonstrated in a real case study located in Portugal.

The application of this methodology for evaluating the case study has demonstrated the usefulness of the methodology for answering the research questions under study in this project. Moreover, even though more case studies should be evaluated to have answer comparably to other countries, the evaluated case study presents also interesting conclusions related to the mentioned research questions applied in the specific conditions in Portugal, as the case of Picoto neighbourhood. In particular, there are insights that can be drawn from this research that can address research questions 1, 2 and 3 (RQ1, RQ2 and RQ3). In relation to RQ1, importantly, Centralised Heat Pump + Photovoltaic and Centralised Biomass Boiler system solutions can lead the Picoto neighbourhood to an energy and carbon emissions neutrality, while maintaining cost-effectiveness. Regarding RQ2, the study highlights the advantage in terms of energy efficiency as well as costs of considering a centralised approach when addressing a group of building or neighbourhood such as the case study investigated here. In relation to RQ3, the study allowed for the indication of the efficiency of the energy supply system as one of the key factors for the cost-effectiveness of the balance between energy efficiency measures and renewable energy supply.

Although results are clearly related to the particular context of Portugal, the study is useful for demonstrating the applicability of the methodology. Moreover, results indicating that heating demand in this type of climate can be lower than in Northern Europe (where district heating for example, is widely disseminated) can be useful to understand the cost-effectiveness of centralised solutions and local heating network systems addressing neighbourhoods, in particular for southern countries in Europe as well. To comprehensively validate the methodology presented here, it is important to investigate other contextual settings and pre-existing situations, as this project plans to do in a next step. A deeper assessment of expected uncertainties, such as specificities in terms of the evolution of energy costs depending on the national context is also recommendable for future studies. This will also allow obtaining general trends and conclusions comparably to different countries and regions, regardless of their climate conditions and other specific conditions.

CRediT authorship contribution statement

Jon Terés-Zubiaga: Writing - original draft, Methodology, Conceptualization. **Roman Bolliger:** Conceptualization, Methodology, Writing - review & editing. **Manuela G. Almeida:** Project administration, Supervision, Writing - review & editing. **Ricardo Barbosa:** Software, Formal analysis. **Jørgen Rose:** Writing - review & editing. **Kirsten E. Thomsen:** Writing - review & editing. **Eduardo Montero:** Software. **Raúl Briones-Llorente:** Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] European Commission, Energy, transport and environment indicators. Eurostat (2012).
[2] IPCC, Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) 144 pp.
[3] 2020 Climate and energy package—European Commission, https://ec.europa.eu/clima/policies/strategies/2020_en (2017).
[4] 2030 Climate and energy framework — European Commission., https://ec.europa.eu/clima/policies/strategies/2030_en (2018).
[5] European Commission, Directive 2012/27/EU on Energy Effciency (2012).
[6] European Commission, Directive 2010/31/EU on the Energy Performance of Buildings (2010).
[7] O. Morck, M. Almeida, M. Ferreira, N. Brito, K.E. Thomsen, I. Østergaard, Shining Examples Analysed within the EBC Annex 56 Project, Energy Procedia 78 (2015) 2334–2339.
[8] S. Paiho, J. Ketomäki, L. Kannari, T. Häkkinen, J. Shemeikka, A new procedure for assessing the energy-efficient refurbishment of buildings on district scale, Sustainable Cities and Society. 46 (2019) 101454.
[9] O. Mørck, M. Almeida, M. Ferreira, N. Brito, K.E. Thomsen, I. Østergaard, Shining examples analysed within the EBC Annex 56 project, Energy Build. 127 (2016) 991–998.
[10] S. Domingo-Irigoyen, A. Sánchez-Ostiz, J.S. Miguel-Bellod, Cost-effective Renovation of a Multi-residential Building in Spain through the Application of the IEA Annex 56 Methodology, Energy Procedia 78 (2015) 2385–2390.
[11] Å. Blomsterberg, E. Pedersen, Tenants Acceptance or Rejection of Major Energy Renovation of Block of Flats – IEA Annex 56, Energy Procedia 78 (2015) 2346–2351.
[12] K.E. Thomsen, J. Rose, O. Morck, S.Ø. Jensen, I. Østergaard, Energy Consumption in an Old Residential Building Before and After Deep Energy Renovation, Energy Procedia 78 (2015) 2358–2365.
[13] M. Almeida, M. Ferreira, Cost effective energy and carbon emissions optimization in building renovation (Annex 56), Energy Build. 152 (2017) 718–738.
[14] F. Cappelletti, T.D. Mora, F. Peron, P. Romagnoni, P. Ruggeri, Building Renovation: Which Kind of Guidelines could be Proposed for Policy Makers and Professional Owners?, Energy Procedia 78 (2015) 2366–2371.
[15] IEA EBC Annex 75, IEA EBC Annex 75 - Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables.
[16] J.S. Mira Conci, A District Approach to Building Renovation for the Integral Energy Redevelopment of Existing Residential, Areas. 9 (5) (2017) 747–759.
[17] European Commission, Commission Recommendation (EU) 2019/786 of 8 May 2019 on building renovation (2019).
[18] European Commission, Directive (EU) 2018/844 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (2018).
[19] S.S. Castro, M.J. Suárez López, D.G. Menéndez, E.B. Marigorta, Decision matrix methodology for retrofitting techniques of existing buildings, J. Cleaner Prod. 240 (2019) 118153.
[20] V. D'Alonzo, A. Novelli, R. Vaccaro, D. Vettorato, R. Albatici, C. Diamantini, P. Zambelli, A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale, Energy Build. 206 (2020) 109581.
[21] S. Ferrari, F. Zagarella, P. Caputo, A. D'Amico, Results of a literature review on methods for estimating buildings energy demand at district level, Energy. 175 (2019) 1130–1137.
[22] S. Ferrari, F. Zagarella, P. Caputo, M. Bonomolo, Assessment of tools for urban energy planning, Energy. 176 (2019) 544–551.
[23] W. Ott, R. Bolliger, V. Ritter, S. Citherlet, S. Lasvaux, D. Favre, B. Périsset, M. Almeida, M. Ferreira, S. Ferrari, Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56). Report produced within the IEA's Energy in Buildings and Communities Programme, Annex 56, http://www.iea-annex56.org/ [Last accessed 2019-06-06] (2017).
[24] A. Kylili, P.A. Fokaides, P.A. Lopez Jimenez, Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review, Renew. Sustain. Energy Rev. 56 (2016) 906–915.
[25] ISO 52016-1, Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures (ISO 52016-1:2017) (2017).
[26] European Commission, Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing Directive 2010/31EU on the energy performance of buildings, establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements (2012) L 81/18-L 81/36.
[27] European Commission, EU Reference Scenario 2016. Energy, transport and GHG emissions trends to 2050 (2016).
[28] E. Cuerda, O. Guerra-Santin, J.J. Sendra, F.J. Neila, Understanding the performance gap in energy retrofitting: Measured input data for adjusting building simulation models, Energy Build. 209 (2020) 109688.
[29] Instituto Nacional de Estatistica, Inquérito à Caracterização da Habitação Social relativo a 2015 (Retrieved December 12, 2018, from: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_destaques&DESTAQUESdest_boui=250034590&DESTAQUESmodo=2&xlang=pt) (2015).
[30] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263.
[31] Climate-Data.org, Climate-Data Braga. Available online:https://pt.climate-data.org/europa/portugal/braga/braga-131/ (accessed on 26 March 2020) (2020).
[32] R. Barbosa, R. Vicente, R. Santos, Climate change and thermal comfort in Southern Europe housing: A case study from Lisbon, Build. Environ. 92 (2015) 440–451.
[33] República Portuguesa, Decreto-Lei n.o 118/2013—Regulamento de Desempenho Energético dos Edifícios de Habitação (REH). Diário da República 1.a série, N.o 2013 (159) (2013) 4988–5005.
[34] DOE. Energy Plus v9.3.0. US Department of Energy. Available online: http://energyplus.net (accessed on 4 March 2020). (2020).
[35] S.A. CYPE Ingenieros, Gerador de Preços. Portugal. Available online: http://www.geradordeprecos.info/ (accessed on 4 March 2020). (2020).
[36] Fundação Francisco Manuel dos Santos, PORDATA – Base de Dados Portugal Contemporaneo. Available online: https://www.pordata.pt/ (Accessed on 4 March 2020) (2020).
[37] International Energy Agency, World Energy Outlook 2019. (2019).
[38] European Commission, EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050 Main results. (2016).
[39] República Portuguesa. Portaria n.º 98/2019— Metodologia de determinação da classe de desempenho energético. Diário da República n.º 65/2019, Série I de 2019-04-02.