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A MILP optimization method for energy renovation of residential urban areas: Towards Zero Energy Districts

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ABSTRACT

The nearly Zero Energy Building concept should be adopted in the renovation of existing buildings and actions upscaled and applied to larger and larger urban areas. In this context, this paper presents an optimization methodology for drafting integral renovation actions at district level. The methodology is based on a MILP model that allows selecting energy saving measures, as well as the design and operation of energy supply systems amongst a very large set of potential permutations. For its application, the concept of District Equivalent Building is introduced, defined as a virtual building with a set of energy loads equal to the addition of all the individual load vectors of each building.

The methodology was applied to a real residential district located in Bilbao (northern Spain). For this case study, the optimal renovation plan was obtained, considering for that three different optimization objectives: (i) Optimal-Cost, (ii) Zero Energy District (ZED) and (iii) Zero Energy District including domestic electricity consumption in the calculation of the non-renewable primary energy consumption (ZED'). Although similar solutions were adopted for each of these cases, significant differences were get attending the hourly operation of the solutions. These cases were economically assessed and the optimal-cost curve was obtained.

1. Introduction

The current climate crisis makes it pressing to take measures in order to improve the energy performance of the building stock. An important milestone focusing this challenge on the path towards more efficient building stock was the EPBD recast (European Commission, 2010), which aimed to cut the overall primary energy consumption of the European building stock. This Directive introduced two important concepts: cost-optimality and the nearly Zero Energy Buildings (nZEB), as well as it sets as its main goal that all new buildings and part of the existing stock to be nearly Zero Energy Buildings. Thus, building design, typically covering envelope, energy systems and the interactions between both of them, is a key issue to be considered when certain levels of performance are to be reached.

However, considering the relatively low specific consumption of individual buildings and the economies of scale existing in the building sector, nowadays is more and more common to move beyond the individual boundary, applying the nZEB principle to the intermediate urban scale or *district*, from an architectural and urban planning perspective. Additionally, by establishing the zero-energy objective to the overall district, the strategy of considering the contributions from different energy performances and different production capabilities allows to take advantage of diversity and opens the possibility for sharing needs, costs and resources (Amaral, Rodrigues, Rodrigues Gaspar, & Gomes, 2018). Therefore, the Directive 2012/27/EU on energy efficiency (European Commission, 2012) highlighted the significant potential for saving primary energy of district heating and cooling systems, and it urged the Member States to carry out a comprehensive assessment of this potential. This has given rise to the concept of Zero Energy Districts (from now

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Nomenclature

Sets and indices

B	Buildings (b)
C	Clusters of buildings (c)
K	Technologies (k)
K_{ESM}	Energy Saving Measures as virtual technologies ($K_{ESM} \subseteq K$) (k)
K_{MAN}	Manageable technologies ($K_{MAN} \subseteq K$) (k)
K_{FR}	Technologies with full load regulation ($K_{FR} \subseteq K$) (k)
K_{RR}	Technologies with restricted load regulation ($K_{RR} \subseteq K$) (k)
S	Modules (s)
S_{NE}	Modules, excluding electricity ($S_{NE} \subseteq S$) (k)
F_{MAN}	Manageable fuels (f)
F_{NMAN}	Non-manageable fuels (f)
D	Reference days (d)
H_d	Intervals in a reference day (h)
J	Facility location (j)

Decision variables

n_k	Number of installed units of a technology
$u_k^{d,h}$	Commitment state of a unit
$e_{s,k,d,h}^{OUT}$	Total produced energy (kWh/h)[11]
$e_{s,k,d,h}^{IN}$	Total consumed energy (kWh/h)
$e_{s,d,h}^{BUY}$	Energy bought by the system (kWh/h)
$e_{s,d,h}^{SELL}$	Energy sold by the system (kWh/h)
$e_{s,d,h}^{STO}$	Energy transferred to storage (kWh/h)
$e_{f,k,d,h}^{MAN}$	Manageable fuel input (kWh/h)
$q_s^{d,h}$	Stored energy at the beginning of the interval (kWh)

Constant parameters

ψ	Orientation of the building
A	Area
N_d	Yearly number of days of a reference day
$L_s^{d,h}$	Load (kWh/h)
L_s^{PEAK}	Maximum load (kW)
q_s	Annual specific load of a building (kWh/m^2)
$\overline{L}_s$	Annual heating load (kWh)
DD	Annual degree days
$DD^{d,h}$	Hourly degree days
T_{SP}	Temperature set point (ºC)
T_B	Base temperature for the building (ºC)
$T^{d,h}$	Hourly temperature (ºC)
C_{log}	Binary control variable
$E_{s,k}^{MAX}$	Production at maximum power (kW)
$E_{s,k}^{MIN}$	Production at minimum power (kW)
$E_{s,k,d,h}^{ESM}$	Contribution of an Energy Saving Measure as virtual technology $k \in K_{ESM}$ (kWh/h)
$Q_{s,k}^{MAX}$	Maximum storage capacity (kWh)
$NRPE^{LIM}$	Non-renewable primary energy consumption limit, excluding electricity (kWh/y)
$NRPE'^{LIM}$	Non-renewable primary energy consumption limit, including electricity (kWh/y)
A_j^{MAX}	Available area in a facility location (m^2)
$A_{j,k}$	Facility location area used by a technology unit (m^2)
W_s	Module based primary energy weighting factors
$W_{s,k}$	Module and technology based primary energy weighting factors
$E_{f,k,d,h}^{NMAN}$	Non-manageable fuel input (kWh/h)
p_k	Principal output module of a technology ($p_k \in S$)
η_s^Q	Storage efficiency
$\eta_{s,k}^{OUT}$	Production ratio with respect to the principal
$\eta_{s,k}^{IN}$	Consumption ratio with respect to the principal
$\eta_{f,k}^{MAN}$	Manageable fuel input ratio with respect to the principal
$\eta_{f,k}^{NMAN}$	Non-manageable fuel input ratio with respect to the principal
C_k^{INV}	Initial investment cost (€)
C_s^{BUY}	Purchase cost (€/kWh)
C_s^{SELL}	Sale income (€/kWh) C_f^{MAN} Purchase cost of manageable fuels (€/kWh)

on ZED), a concept that has awakened more and more interest during the las few years, leading to numerous papers on this field.

Amaral et al. carried out a review of the literature with the aim of identifying those urban elements that can be considered key on the district's performance, such as morphology, climate and availability of public spaces (Amaral et al., 2018). R. Aghamolaei et al. conducted a review on different approaches for energy performance evaluation of districts, focusing on three issues: concepts defining district energy performance, approaches and methodologies, and system interactions between district entities (Aghamolaei, Shamsi, Tahsildoost, & O'Donnell, 2018). Koutra et al. presented an overview of the existing assessment tools and methods comparing their criteria and key parameters (Koutra, Becue, Gallas, & Ioakimidis, 2018), introducing, as a result, a simplified methodological assessment theoretical tool (U-ZED) focused on the commitment towards the zero energy targets in a future district. J. Reynolds et al. focused a review on control systems for optimisation in buildings at building and district level, argues for the upscaling of building control and optimisation to a wider district level (Reynolds, Rezgui, & Hippolyte, 2017). Ma et al. conducted a review study of district heating system components, markets and the energy flexibility potentials in district heating (Ma, Knotzer, Billanes, & Jørgensen, 2020). A survey was proposed to investigate the stakeholder's perception and motivation on smart district heating grids using energy flexible buildings. All these reviews show that the growing interest on energy assessment at community or district scale has been significant in recent years. Amongst them, several of these assessments focus on developing district-scale methodologies and procedures analysing or identifying energy-efficient renovation of buildings and/or different case studies can be found in the literature in recent years (Abdurafikov et al., 2017; Paiho, Abdurafikov, & Hoang, 2015; Paiho, Abdurafikov, Hoang, & Kuusisto, 2015; Paiho, Ketomäki, Kannari, Häkkinen, & Shemeikka, 2019; Terés-Zubiaga et al., 2020; Zajacs & Borodiņecs, 2019).

As design is a key aspect for enhancing the energy performance at the district level, there is an intrinsic need for optimization. In line with this, Sameti and Haghighat have recently presented a review paper where different types of optimization problems, constraints and techniques as well as the optimization tools used in district energy systems are discussed (Sameti & Haghighat, 2017). These optimization problems are applied to different levels: (i) actions on the energy supply system of the district, i.e. by a district heating/cooling network and (ii) integral actions at district level including the design of buildings as well as their energy supply system.

Amongst those dealing with the design and operation of district heating and cooling networks, Wirtz et al. proposed a novel design methodology based on Linear Programming for designing and evaluating distributed energy systems with bidirectional low temperature networks (Wirtz, Kivilip, Remmen, & Müller, 2020). Analogously, Best et al. presented a mixer integer linear programming (MILP) methodology for district heating optimization, which is applied to 3 case studies (Best, Rezazadeh Kalehbasti, & Lepech, 2020). Complementary to these works, Sameti and Haghighat paid special attention to the effect of distributed thermal energy storage systems, presenting a method that allows integrating them within district thermal networks (Sameti & Haghighat, 2018), similarly to that proposed by Joly et al. for the integration of solar thermal systems (Joly et al., 2017) or Dénarie et al. for industrial waste heat recovery (Dénarié, Muscherà, Calderoni, & Motta, 2019). Additionally, in the field of the development of new algorithms, Hohmann et al. presented a stochastic polynomial optimization problem to derive high-performance operating strategies for heating networks with uncertain or variable demand (Hohmann, Warrington, & Lygeros, 2019) and Ikeda and Ooka compared several algorithms for district heating optimization proposing the so-called constrained differential evolution with random jumping II (Ikeda & Ooka, 2019).

Regarding the integral design of low energy districts, several authors have proposed different approaches focused on diverse optimization techniques. Kalaycıoğlu and Yılmaz analysed nearly zero energy levels firstly in buildings and next in the district scale by implementing the further energy efficiency measures, such as the use of district heating/cooling systems and the installation of renewable energy technologies in addition to those installed on-site (Kalaycıoğlu & Yılmaz, 2017). In line with this, Paiho et al. introduce a novel district-scale procedure for analysing energy-efficient refurbishment of buildings (Paiho et al., 2019). Hansen et al. evaluated interrelations between high efficiency district networks and energy saving measures at building level. The overall outcome of this study is that, in Denmark, a new district heating system is competitive compared to individual heating solutions (Hansen, Gudmundsson, & Detlefsen, 2019). More orientated to decision making, Becchio et al. developed a planning methodology based on cost-benefit analysis of different actions at district scale, which is lately applied to the design of a Zero Energy District in Turin (Becchio, Bottero, Corgnati, & Dell'Anna, 2018). In the field of the development of new algorithms, Bucking and Dermadiros proposed a new methodology that co-optimizes building designs and district technologies as an integrated community energy system. A distributed evolutionary algorithm is proposed for this purpose, which can navigate over 10^{154} potential permutations (Bucking & Dermardiros, 2018). Amongst previously mentioned studies several optimization methods can be distinguished, namely, parametric, genetic algorithms, Monte Carlo analysis and mathematical programming (Hashempour, Taherkhani, & Mahdikhani, 2020). Amongst these, mathematical programming, specifically, MILP methods have largely been applied to building design and operation, especially due to the fast resolution times, which allow preliminary designs or starting points for more detailed analysis.

In this sense, this paper continues the work previously developed by the authors. Firstly, a MILP-based optimization method was developed with the aim of identifying optimal solutions for the design and operation of energy supply systems (Iturriaga, Aldasoro, Campos-Celador, & Sala, 2017). Secondly, this method was upgraded in order to include energy savings measures, enabling the application for retrofitting of buildings (Iturriaga, Aldasoro, Terés-Zubiaga, & Campos-Celador, 2018). In both cases, the optimization method was used to provide optimal solutions for individual buildings. This paper deals with the adaptation of that model for its application at district scale, exploring the potential to get ZEDs. For that aim, the concept of District Equivalent Building was introduced, defined as a virtual building accounting for the overall energy demand of the district. Thus, this paper present an optimization strategy for the renovation of districts with the aim of meeting different Non-Renewable Primary Energy (NRPE) consumption limits, considering additional constraints such as economic issues or space availability, amongst others.

It should be highlighted that the tool is not conceived for reaching the accuracy of advanced dynamic simulation softwares for evaluating building energy performance, but to provide a first approach, which allows to carry out systematic and fast scans in order to identify a first set of optimal solutions for planning renovations at district level. In other words, this is not a precision tool, but a planning tool for obtaining reliable results. Thus, unlike other approaches in the literature, the methodology presented here consists of a fast and simple-to-apply method that enables the optimization of both design and operation of the complete retrofitting action. For that aim, the MILP model does not consider the dynamic behaviour of the ESS and, instead of simulate a large number of configurations, any solution is a discrete representation of a larger superstructure. One of the advantages, when compared to other approaches in the literature, is the large set of retrofitting actions under consideration, covering both Energy Supply Systems (ESS) and energy saving measures (ESM). The proposed methodology was subsequently applied to a case study, consisting in the residential district of Otxarkoaga in Bilbao (northern Spain), for which the optimal design and operation was determined for three NRPE consumption scenarios: Cost-Optimal, Zero Energy District (ZED) and Zero Energy District considering all the domestic electricity consumption in the NRPE calculation (ZED').

The rest of this paper is organised as follows: in Section 2 the main features of the optimisation methodology is presented. The model is applied to the case study described in Section 3, identifying the optimal configuration and operation, as Section 4 details. Finally, conclusions of the study, as well as future works are summarised in Section 5.

2. Materials and methods

In this Section, a methodology for the optimal renovation of districts is presented. The proposed methodology, based on previous research by the authors (Iturriaga et al., 2017, 2018), aims to optimize both ESM and ESS of districts to meet several NRPE consumption objectives. As presented before, this requires the previous definition of the District Equivalent Building, a virtual building adding the energy needs of the whole district that is obtained as follows.

2.1. District equivalent building

The optimization method offers the optimal design and hourly operation of the ESS for a given set of energy demands. These energy demands are inputs by the user and therefore, independent to the level of aggregation; in other words, the summation of the loads is equivalent to the overall load of the district, which lead us to define a District Equivalent Building (DEB). Of course, this requires these loads to be exactly met at any time, which is ensured by the equations governing the energy balances (Section 2.2)

To define this DEB, a building inventory of the district is required. It should be noted that different uses of buildings will present different features and required related to energy needs and energy carriers. For the sake of the clarity, this paper focus on the implementation of the methodology on a residential district, so all the analysis will be carried out considering the specificities of residential buildings. This should contain the following qualitative and quantitative categories for any building: roof area (A_R), conditioned area (A), building perimeter (P), percentage of windows or windows-to-wall ratio (W), number of floors (F) and orientation (ψ). Additionally, all the buildings within the district (let B be the set of clusters) are clustered considering the construction typology (let C be the set of clusters). These clusters include all those buildings sharing the same construction characteristics and therefore, new typologies should be created if specific retrofitting actions have been applied in the past to part of the stock.

Even though this can be get by different means, GIS tools can be

[1] This unit represent the amount of energy (in kWh) generated or used in a 1-hour period. Since the methodology presented is open to be used with different time-steps, this generic notation has been used.

Table 1
List of the equations integrated in the MILP model.

Category	Description	Equation	
	Energy balance for each module	$\sum_{k\in K} e^{OUT}_{s,k,d,h} + e^{BUY}_{s,d,h} - \sum_{k\in K} e^{IN}_{s,k,d,h} - e^{SELL}_{s,d,h} - e^{STO}_{s,d,h} = L^{d,h}_s \quad \forall s\in S, d\in D, h\in H_d$	Eq. 5
	Energy balance for thermal energy storage systems	$\sum_{k\in K_{MAN}} E^{MAX}_{s,k}\cdot n_k \geq L^{PEAK}_s \quad \forall s\in S$	Eq. 6
		$q^{d,0}_s = 0 \quad \forall s\in S, d\in D$	Eq. 7
	Energy balances for storage systems	$q^{d,h}_s + e^{STO}_{s,d,h} = \eta^Q_s q^{d,h+1}_s \forall s\in S, d\in D, h\in H_d \| 0 < h < \|H_d\|$	Eq. 8
		$q^{d,\|H_d\|}_s + e^{STO}_{s,d,\|H_d\|} = 0 \quad \forall s\in S, d\in D$	Eq. 9
		$q^{d,h}_s \leq Q^{MAX}_s \cdot n_{TES_s} \quad \forall s\in S, d\in D, h\in H_d$	Eq. 10
		$e^{OUT}_{p_k,k,d,h} = \eta^{OUT}_{s,k}\cdot e^{OUT}_{s,k,d,h} \quad \forall s\in S, k\in K, d\in D, h\in H_d$	Eq. 11
	Energy balance at the technology level	$e^{OUT}_{p_k,k,d,h} = \eta^{IN}_{s,k}\cdot e^{IN}_{s,k,d,h} \quad \forall s\in S, k\in K, d\in D, h\in H_d$	Eq. 12
		$e^{OUT}_{p_k,k,d,h} = \eta^{MAN}_{f,k}\cdot e^{MAN}_{f,k,d,h} \quad \forall f\in F_{MAN}, k\in K, d\in D, h\in H_d$	Eq. 13
Energy		$e^{OUT}_{p_k,k,d,h} = \eta^{NMAN}_{f,k}\cdot E^{NMAN}_{f,k,d,h} \quad \forall f\in F_{NMAN}, k\in K, d\in D, h\in H_d$	Eq. 14
		$e^{OUT}_{s,k,d,h} \leq E^{MAX}_{s,k}\cdot n_k \quad \forall s\in S, k\in K_{FR}, d\in D, h\in H_d$	Eq. 15
	Production limits for the technologies	$E^{MIN}_{s,k}\cdot u^{d,h}_k \leq e^{OUT}_{s,k,d,h} \leq E^{MAX}_{s,k}\cdot u^{d,h}_k \quad \forall s\in S, k\in K_{RR}, d\in D, h\in H_d$	Eq. 16
		$u^{d,h}_k \leq n_k \leq 1 \quad \forall k\in K_{RR}, d\in D, h\in H_d$	Eq. 17
	Virtual energy production of the ESM	$e^{OUT}_{s,k,d,h} = E^{ESM}_{s,k,d,h} \quad \forall s\in S, k\in K_{ESM}, d\in D, h\in H_d$	Eq. 18
		$\sum_{k\in K_{ESM}} n_k \leq 1$	Eq. 19
	Peak load reduction of the ESM	$\sum_{k\in K_{MAN}} E^{MAX}_{s,k}\cdot n_k \geq \max_{d,h}\left(L^{PEAK}_s - \sum_{k\in K_{ESM}} n_k\cdot E^{ESM}_{s,k,d,h}\right) \quad \forall s\in S$	Eq. 20
	Temperature profile for reference days	$T^{d,h} = T^d_M + \left(T^d_{MAX} - T^d_{MIN}\right)\cdot \sum_{j=1}^4 a_j\cdot \cos(j\cdot\tau^t - b_j)$	Eq. 21
	Definition of Hourly Degree Days	$DD^{d,h} = \left(T_{SP} - T^{d,h}\right) {C_{log}}^{d,h}$	Eq. 22
	Distribution of the overall heating thermal load	$L^{d,h}_{LT} = \frac{DD^{d,h}\cdot\frac{N_d}{24}}{DD}\overline{L}^{DEB}_{LT}$	Eq. 23
		$\mathrm{C}^{\mathrm{annual}} = \frac{1}{LS}\left[\mathrm{C}^{\mathrm{INI}} + \sum_{i=0}^{LS}\left(C^{OP}_i\cdot R_i\right) - V\right]$	Eq. 24
		$\mathrm{C}^{\mathrm{INI}} = \sum_{k\in K} C^{INV}_k\cdot n_k\cdot\left(1 + f^{O\&M}_k\right)$	Eq. 25
Economics	Determination of the annual cost	$C^{OP}_i = \sum_{d\in D} N_d \sum_{h\in H_d}\left[\sum_{s\in S}\left(C^{BUY}_s\cdot e^{BUY}_{s,d,h} - C^{SELL}_s\cdot e^{SELL}_{s,d,h}\right) + \sum_{f\in F_{MAN}}\sum_{k\in K} C^{MAN}_f\cdot e^{MAN}_{f,k,d,h}\right]$	Eq. 26
		$R_i = (1+r)^{-i}$	Eq. 27
		$\mathrm{V} = \sum_{k\in K} C^{INV}_k\cdot n_k\cdot\left(\frac{LS_k}{LS} - 1\right)\cdot\frac{1}{(1+\mathrm{r})^{\mathrm{LS}}}$	Eq. 28

useful to prepare the inventory. This inventory will be subsequently used to determine, in an annual basis, the building loads of the District Equivalent Building.

Thermal loads of the District Equivalent Building, namely heating lod (L^{DEB}_{heat}), are get from the yearly specific heating loads, which depends on the building typology and orientation, $q^C_{heat}(\psi)$ (kWh/m^2 year). Considering the orientation of each building and the building cluster that they belong to, the District Equivalent Building heating load can be obtained. While typology and orientation can be easily get from the vector map of the district, the specific heating load of each building typology is needed as input data, which, additionally, depends on the orientation of each building. Hence, the heating load of the district is obtained considering the conditioned area of each building.

$$\overline{L}^{DEB}_{HEAT} = \sum_{c\epsilon C}\sum_{b\in c} q^c_{HEAT}\left(\psi^b\right)\cdot A^b \tag{1}$$

Domestic hot water (DHW) load is usually calculated considering a certain water volume per inhabitant plus a reference temperature leap for DHW production. As occupancy is usually related to the conditioned area, a general specific demand can be defined (q_{DHW}) and the District Equivalent Building DHW load, L^{DEB}_{DHW}, calculated as follows:

$$\overline{\boldsymbol{L}}^{DEB}_{DHW} = \sum_b \boldsymbol{q}_{DHW}\cdot\boldsymbol{A}^b \tag{2}$$

Analogously, the electricity load of the District Equivalent Building can be determined from a general specific electricity demand.

$$\overline{\boldsymbol{L}}^{DEB}_{ELE} = \sum_b \boldsymbol{q}_{ELE}\cdot\boldsymbol{A}^b \tag{3}$$

ESM encompasses renovation actions on different elements (let K_{ESM} be the set of ESMs). However, these usually consist windows, facade and/or roof. Thus, the investment can be presented as a function of the ESM area (A_{ESM}), which is ($P\cdot H\cdot W$) for windows, ($P\cdot H\cdot(1-W)$) for facades and (A_{ROOF}) for roofs and the specific cost for each ESM, resulting in the following:

$$\boldsymbol{C}^{INV}_{ESM} = \sum_{k\in K_{ESM}} \boldsymbol{C}^{INV}_{ESM}\cdot\boldsymbol{A}^k_{ESM} \tag{4}$$

2.2. Energy supply systems and energy savings measures

The modelling of ESS and ESMs was developed and presented by the authors in previous papers, therefore, the reader is referred to them for a more detailed description (Iturriaga et al., 2017, 2018). With the aim of facilitating the readability of the paper, the main equations of the MILP model are summarized in Table 1.

The ESSs are modelled considering a general superstructure where all the potential energy system design and operation permutations for any district are comprised (Fig. 1a). The four interlinked modules considered in it (Electricity, High-, Medium- and Low-Temperature Heating) provide the energy needs for DHW, heating and electricity of the District Equivalent Building. Thus, this approach allows including any possible energy supply system configuration, both existing and future technology developments for any of the considered modules. As the methodology is intended for full districts, only district heating network is considered for thermal energy supply. Regarding the topology of the network, although several alternatives could be considered in the optimization problem, as each one represents a fixed cost to the energy supply system, it is foreseeable that an optimization of it is

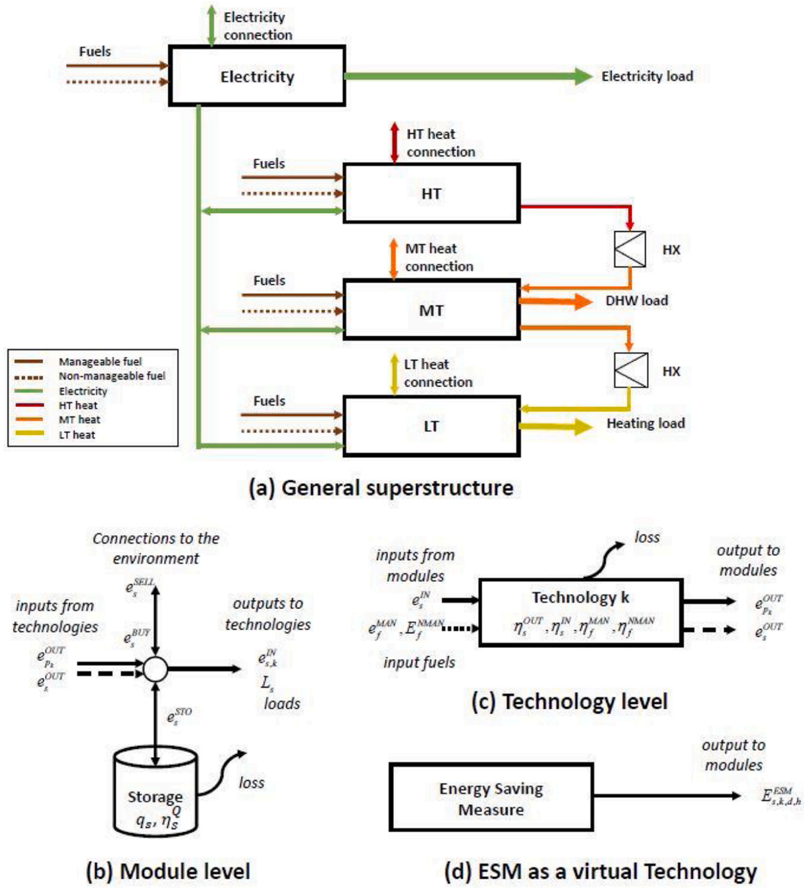

Fig. 1. Schematic view of the model (based on the presented in (Iturriaga et al., 2018)).

carried out before, using the resulting configuration as an input to the here presented optimization model.

The different energy loads are the outputs from the modules (see Fig. 1b). Thus, electricity load is output from the electricity module and heating and DHW are outputs from, respectively, the High, Medium and Low Temperature Heating modules. Each module includes all the possible technologies with the same main product. They also may include a storage device that enables decoupling production and load. Hence, Eq. 7 describes the energy balance for each model at every interval h of every reference day d. Similarly, manageable peak power, the energy balance in storage systems and the upper bound for the storage power based on the storage capacity are described by Eq. 8. As it can be seen in Fig. 1, each module can include a certain storage capacity, whose hourly operation is defined from Eqs. 9–12.

Technologies are defined as black boxes that related energy outputs with the required energy consumption or fuels. Each technology has a main product (p_k), defining the rest of the inputs and outputs in relation to it by specific ratios, as presented from Eqs. 13–16. Their definition is enough flexible to cover multi-fuel and multi-output technologies, such as cogeneration units. As far as fuels are concerned, they are classified as manageable or non-manageable. One example of the latter is the solar irradiation, where the availability is external to the needs of the system. The production of each technology can vary from 0 to its nominal power, according to Eq. 17. However, it is possible to limit the regulation capacity of some technologies, such as cogeneration, including a minimum partial load, which is include in Eq. 18 and Eq. 19.

All these modules are interconnected, allowing the outputs of some modules to be the inputs for others. At the same time, every module presents a bidirectional connection with the environment, enabling the energy to be bought from a source or sold to a sink. Moreover, High and Medium Temperature modules present a bidirectional link with the electricity module, in order to enable the possibility of considering electricity-driven or electricity production technologies.

The implementation of any package of ESM involves a reduction in the heating load to be met by any ESS at any time interval. To include this effect in the previously described superstructure, ESM are represented by "virtual technologies", integrated into the module of the load they contribute to reduce. Thus, based on the technology representation depicted in Fig. 1c, any ESM could be represented as Fig. 1d. The virtual production corresponding to each ESM will contribute to the energy production of the module from which space heating load is supplied, being this production non-manageable by the user (Eq. 20). Besides, the implementation of any ESM will also involve a reduction of the peak load of manageable technologies to be installed (see Eq. 22). Finally, any ESM is an integral renovation action on the envelope, so the selection of a specific ESM will imply necessarily discarding the others (Eq. 21).

Load reduction and load peak reduction resulted from the implementation of a given ESM can be provided either by a detailed simulation or other estimations. Yearly demand is distributed into time intervals, and a compromise on the overall amount of intervals should be obtained between the level of detail and simplicity. Looking for finding that compromise, a degree-day based simple method is proposed for simplifying load curves, considering that the new load resulting from the implementation of an ESM is distributed in a different way to that of the initial scenario. This method is developed for space heating. Hence, temperature profile for each monthly reference day is built as Erbs et al. presented in Erbs, Klein, and Beckman (2003), as Eq. 23 describes. From this temperature profile, the daily degree-days distribution can be easily calculated (see Eq. 24). In order to avoid a load peak during the night (when the lowest outdoor temperatures are, but users are normally sleeping), different temperature setpoint for the day and night periods are defined when the hourly degree-days are calculated. Even though, as

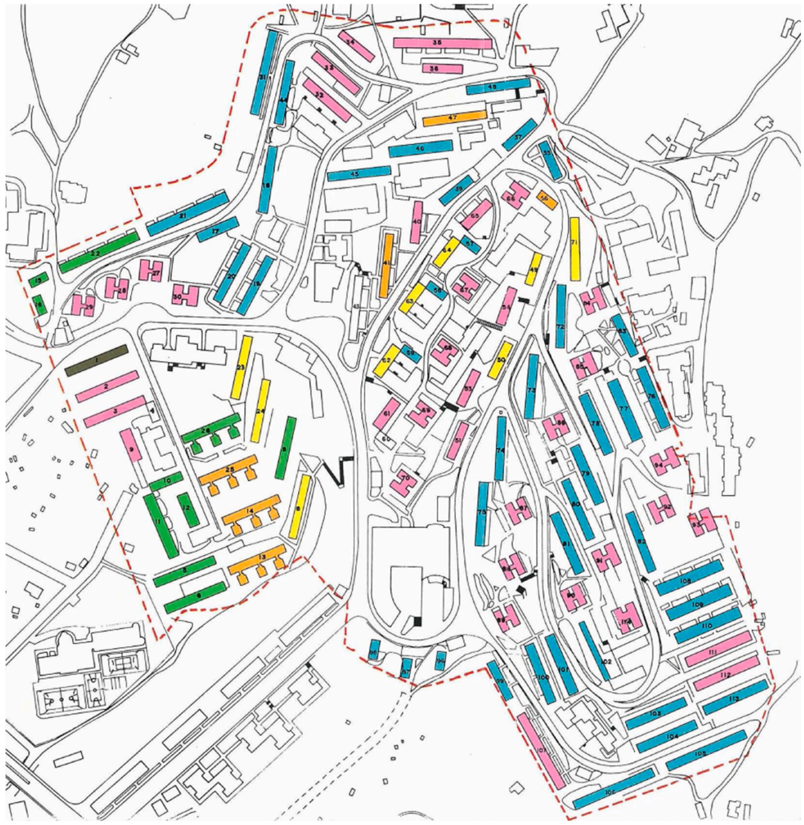

Fig. 2. Layout of the Otxarkoaga district.

presented in (Iturriaga et al., 2018), this approach has some limitations, it is considered accurate enough for obtaining a reliable distribution of the load. Finally, Eq. 25 distributes the overall heating thermal load by hourly intervals per each reference day.

Next, in order to consider the economic effect consequence of fixed and variable costs of any energy renovation, the methodology proposed by the Building Performance Institute Europe (BPIE) (which at the same time is based on the net present value method defined by the Standard EN 15459) is followed in this model (BPIE, 2010). Thus, the annual cost assuming a specific lifespan is defined in Eq. 26. In it, the initial investment (C^{INI}), the yearly variable cost of each technology (C_I^{OP}), the discount factor (R_i) and the salvage value of each technology (V). The initial investment (C^{INI}), as expressed in Eq. 27, is the sum of the annual amortisation of the technologies (considering both ESM and ESS) as well as those cost related to the district heating, i.e. piping, building of the thermal plant, substations, etc. (C_k^{INV}), multiplied by number the installed units. The maintenance and operation costs are considered by including a percentage of the investment of each technology ($f_k^{O\&M}$), as presented in Eq. 28. The selected values in this case are common average values in Spain, but it can be adapted if necessary to other countries. The yearly variable costs of each technology include the costs and incomes of the system operation as described in Eq. 27. R_i, as well as V are described by Eqs. (29) and (30), respectively. Finally, the optimisation problem is defined by the objective function, which consist in minimizing the annual cost.

$$\min C^{annual} \quad (29)$$

Additionally, the function can be subjected to additional constraints that reduce the mathematica space for potential solutions. Considering the goal of our research, one limit would correspond to the NRPE consumption limit, limiting the space of the solutions to those that meet a maximum NRPE consumption. This equation includes the primary energy weighting factors (W_s and $W_{s,k}$) that allows relating the final energy and the primary energy consumption. These weighting factors are country dependent and are regularly updated. For the case of Spain, the last updates for these factors can be found in (Ministerio de Industria, 2014).

$$\sum_{s\in S_{NE}}\sum_{d\in D}\sum_{h\in H_d}\left[\left(\boldsymbol{e}^{BUY}_{s,d,h}-\boldsymbol{e}^{SELL}_{s,d,h}\right)\cdot \boldsymbol{W}_s+\sum_{k\in K}\boldsymbol{e}^{OUT}_{s,k,d,h}\cdot \boldsymbol{W}_{s,k}\right]\le \boldsymbol{NRPE}^{LIM} \quad (30)$$

3. Case study

The here presented optimization methodology is applied to a case study. The case study is the Otxarkoaga district, a residential district located in the eastern part of Bilbao (northern Spain). The selected area (depicted in Fig. 2) is about 24 ha. The main part of the Otxarkoaga district was entirely built up in barely two years (1959–1961), when 3672 apartments distributed in 114 buildings were projected and constructed, and an important renovation was carried out in the district in the eighties, promoted by the city council. For that reason, the majority of the building stock in the district present similar typology and thermal features. Morevoer, some buildings of the district were previously assessed in other studies, such as (Terés-Zubiaga, Campos-Celador, González-Pino, & Diarce, 2016) (at dwelling scale) or (Terés-Zubiaga, Campos-Celador, González-Pino, & Escudero-Revilla, 2015) (at building scale).The reference building was modeled and evaluated in detail, (the validation of the model is presented in (Terés-Zubiaga et al., 2015)) so information about these buildings is available and accurate. As Bilbao presents a temperate weather, residential buildings do not present cooling needs and therefore, only heating, DHW and electricity is considered.

The information on the building of the district was obtained from "Geo Euskadi" webpage (webpage of the Regional Government where different GIS data is available) (GeoEuskadi, 2020), as well as from Bilbao Social Housing, the public municipal entity that manages social

Table 2
Main features of windows.

Frame (30 %)	U_{frame} [W/m^2 K]	Glass	U_{glass} [W/m^2 K]
Metallic without Thermal Break	5.7	4/6/4	3.44

housing in the city. Even though some buildings have been renovated in the last years, a base case was assumed in this study, which presents the construction features resulting from the renovation works carried out in the eighties. Based on the data provided by Bilbao Social Housing, an U-Value of 0.74 W/m^2 K for façade was assumed, and 2.27 W/m^2 K for the roofs (detail description of the envelop is presented in (Terés-Zubiaga et al., 2015)). The difference between those U-values (the U-value of the façade is significantly lower than the U-value of the roof) is due to the fact that a partial renovation was carried out in the whole district in the 80', and the main actions related to improvement of the thermal behaviour were focused on building façades, with no action on roofs. The main parameters of windows are sumarised in Table 2.

3.1. District equivalent building

With the aim of optimising the demand calculation process, the buildings comprised in the district was classified according to their morphology (see Fig. 3), with the aim of defining the District Equivalent Building afterwards. There are 78 rectangular-shaped buildings (A), 6 square towers (B); 4 "E-shaped" buildings (E), and 15 "H-shaped" buildings (H). The others (indicated as "N type" in Fig. 3) present specific layouts and uses that should be evaluated in a more detailed analysis, and for the sake of clarity, they were out of the scope of this analysis. In any case, the procedure for including them would be analogous.

Regarding the orientation, the majority of the buildings present NW/SE or NE/SW orientations, even though E/W and N/S orientations can be also found, being the last the most unfavourable one. The main

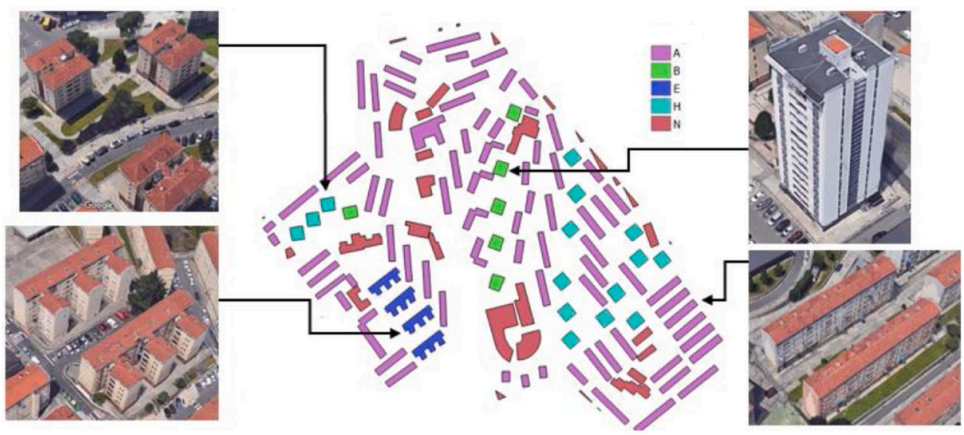

Fig. 3. Identified morphologies in the Otxarkoaga district.

Fig. 4. Orientation of the different buildings evaluated (left) and buildings' height (right).

Table 3
Summary of the main parameters defining the Otxarkoaga district.

Typology (C)	Roof Area (A_{ROOF})	Conditioned Area (A)	Perimeter (P)	Windows to wall percentage (W)	Number of floors (Height - H)	Orientation (ψ)
A (x 78)	162.8–1428.3 m^2	1980.0 m^2	80-115-135 m	≈20 %	6 (3 or 5 in some cases) (8.1-13.5-16.2 m)	NW/SE, NE/SW (E/W and N/S, in some cases)
B (x 6)	346–370.7 m^2	3457.2 m^2	70 m	≈20 %	14 (37.8 m)	–
E (x 4)	710.1–784.1 m^2	3111.5 m^2	180 m	≈20 %	6 (16.2 m)	NW/SE
H (x 15)	346.6–412.4 m^2	1382.9 m^2	100 m	≈20 %	6 (16.2 m)	–

Table 4
Specific heating, DHW and electricity loads for each typology and resulting District Equivalent Building.

Total conditioned area $\sum_{b\in B} A^b$ = 187629.1 m^2 Morphology	HEATING $\overline{q}^c_{LT}$ *(kWh/m^2 year)*	ELECTRICITY $\overline{q}^c_{ELE}$ *(kWh/m^2.year)*	DHW $\overline{q}^c_{DHW}$ *(kWh/m^2. year)*
A	47.81	35	27.47
B	39.56		
E	60.23		
H	47.95		
District Equivalent Building	**44.46**	**35**	**27.47**

orientation for each building is depicted in Fig. 4 (left). In this figure, type B and H buildings (which present a quasi-square layout, and in consecuence, with no prevaling orientation) were identified with a "T".

Regarding the buildings' height, the majority of the type A, H, and E buildings are 6-storey buildings, with some exceptions in type A, where some buildings are 3- or 5-storey buildings. On the other hand, all type B buildings are 14-storey buildings (see Fig. 4, right). The parameters necessary for determining the District Equivalent Building are listed in Table 3 for each of the typologies presented before.

From these parameters, the annual energy needs of the District Equivalent Building can be calculated. the specific space heating load of each typology ($\overline{q}^c_{HEAT}$) was determined by dynamic simulation, specifically, by means of TRNSYS simulation environment. As low temperature radiators were assumed as terminal units, the space heating load is connected to the low temperature (LT) module ($\overline{q}^c_{HEAT} = \overline{q}^c_{LT}$). There are some aspects, such as the relative position of each building in the district and its influence on solar gains that were not taken into consideration in this study, but that could be easily included in the methodology. To assess the effect of the orientation on the space heating demand, a parametric analysis was made performing several TRNSYS simulations, varying its orientation from 0° to 360° with angle steps of 30°. A maximum variation of 6.5 % was found for the worst of the cases (builiding typology A offers, due to its layout, the higher sensitivity to the orientation), so this effect was neglected for the sake of clarity.

DHW and electricity demand is also included assuming standard values, the same for all apartments considering the homogeneity of the district evaluated in this case. Thus, the DHW needs were calculated assuming an average occupation factor of 4 people per apartment, a daily consumption of 28 l/person and a centralization factor of 0.7, as Spanish regulation fixes (Ministerio de Vivienda, 2013). This results in a specific DHW load ($\overline{q}^c_{DHW}$) of 27.47 kW h/m^2. On the other side, an specific electricity load ($\overline{q}^c_{ELE}$) of 35 kW h/m^2 year was assumed, based on statistical data from (EVE (Ente Vasco de la Energía - Basque Energy Agency), 2013). Thus, the specific energy need for every typology, as well as the resulting specific energy needs for the district equivalent building are presented in Table 4.

As a result, the Disitrict Equivalent Building presents a yearly heating load ($\overline{L}^{DEB}_{LT}$) of 8,342,647 kW h/year, a DHW load ($\overline{L}^{DEB}_{DHW}$) of 5,154,171.38 kW h/year and an electricity demand ($\overline{L}^{DEB}_{ELE}$) of 6,567,018.5 kW h/year.

3.2. Energy savings measures

Regarding ESM, 8 different renovation options were considered, selected amongst the 64 different ESMs proposed and evaluated using TRNSYS for that purpose in (Terés-Zubiaga et al., 2015), where also a detailed definition of them can be found. They were considered since they are representative of the different levels of potential improvements in façade, roof and windows (the baseline scenario and three levels of improvement defined in mentioned paper: "Business as usual", "improved scenario" and "high standard renovation"). These criteria were also considered in (Iturriaga et al., 2018).

Thus, the different renovation scenarios are summarised in Table 5, where the thermal properties of the updates, as well as the associated investment, are included. In this case, it was assumed that the same ESM solution was to be applied to all buildings of the district, but partial or progressive application of different solutions could be also implemented in the methodology. The lifespan of the ESMs was set at 50 years and no maintenance cost was considered. As far as area affected by these measures, it encompasses 185,067 m^2 of façades, 43,292 m^2 of roofs, and 44,992 m^2 of windows.

Table 5
ESM scenarios (Iturriaga et al., 2018).

	Windows are not changed		Windows are changed	
Current Building *(no thermal insulation addition in the envelope)*	**SCENARIO 0**		**SCENARIO 4**	
	Current façade (U = 0.74 W/m^2 K)	0 €	**Current façade** (U = 0.74 W/m^2 K)	0 €
	Current Roof (U = 2.27 W/m^2 K)	0 €	**Current Roof** (U = 2.27 W/m^2 K)	0 €
	Current Windows (U = 4.12 W/m^2 K)	0 €	**Windows** 6/12/6 + PVC (U = 2.76 W/m^2 K)	133.28 €/m^2
Renovation "BAU" *(Business As Usual)*	**SCENARIO 1**		**SCENARIO 5**	
	Façade +6 cm thermal ins. (U = 0.43 W/m^2 K)	6.46 €/m^2	**Façade** +6 cm thermal ins. (U = 0.43 W/m^2 K)	6.46 €/m^2
	Roof +6 cm thermal ins. (U = 0.53 W/m^2 K)	10.05 €/m^2	**Roof** +6 cm thermal ins. (U = 0.53 W/m^2 K)	10.05 €/m^2
	Current Windows (U = 4.12 W/m^2 K)	0 €	**Windows** 6/12/6 + PVC (U = 2.76 W/m^2 K)	133.28 €/m^2
Renovation "Improved scenario"	**SCENARIO 2**		**SCENARIO 6**	
	Façade +8 cm thermal ins. (U = 0.36 W/m^2 K)	8.42 €/m^2	**Façade** +8 cm thermal ins. (U = 0.36 W/m^2 K)	8.42 €/m^2
	Roof +14 cm thermal ins. (U = 0.26 W/m^2 K)	20.81 €/m^2	**Roof** +14 cm thermal ins. (U = 0.26 W/m^2 K)	20.81 €/m^2
	Current Windows (U = 4.12 W/m^2.K)	0 €	**Windows** 3/12/3 Low-e + PVC(U = 1.89 W/m^2 K)	176.08 €/m^2
"High standard" Renovation	**SCENARIO 3**		**SCENARIO 7**	
	Façade +14 cm thermal ins. (U = 0.24 W/m^2 K)	14.94 €/m^2	**Façade** +14 cm thermal ins. (U = 0.24 W/m^2 K)	14.94 €/m^2
	Roof +20 cm thermal ins. (U = 0.19 W/m^2 K)	29.11 €/m^2	**Roof** +20 cm thermal ins. (U = 0.19 W/m^2 K)	29.11 €/m^2
	Current Windows (U = 4.12 W/m^2 K)	0 €	**Windows** 4/16/4/16/4/16 + PVC (U = 1.15 W/m^2 K)	212.4 €/m^2

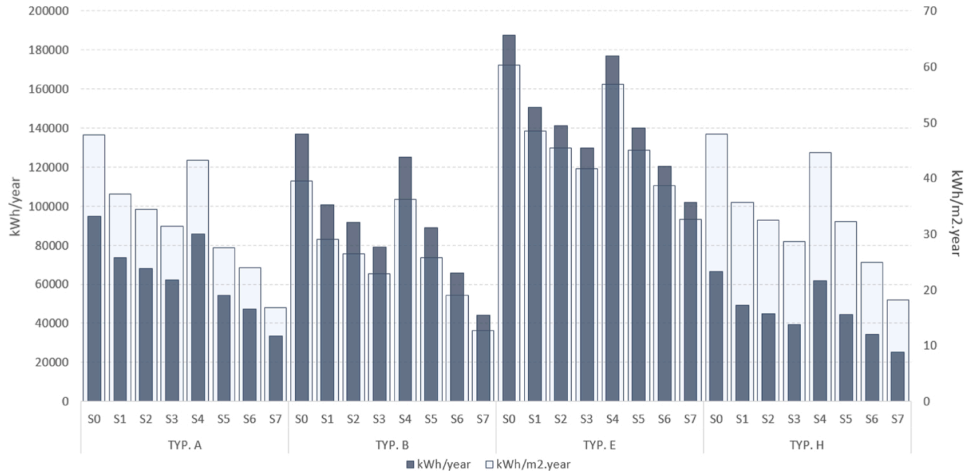

Fig. 5. Space heating load resulting from the ESM scenarios for the different typologies.

Table 6
Aggregated energy demand for heating, electricity and DHW.

Total conditioned area $\sum_{b\in B} A^b =$ 187,629.1 m^2	SPACE HEATING REDUCTION E_{LT}^{ESM} *(kWh/year)*	SPACE HEATING PEAK LOAD L_{LT}^{PEAK} *(kW)*
S0	0	9,260
S1	2,152,636	7,126
S2	2,685,057	6,772
S3	3,410,202	6,398
S4	674,769	7,934
S5	2,828,304	5,799
S6	4,175,215	4,858
S7	5,439,884	3,982

Fig. 6. District heating network proposal.

The implementation of any of these ESM scenarios gave rise to different space heating loads as a function of the building typology. These loads were also determined through TRNSYS software, as it is represented in Fig. 5.

As it is explained in the methodology section, the effect of each ESM scenario was addressed as a virtual thermal energy production equal to the energy reduction that it is get by it (E_{LT}^{ESM}). Taking the data from Fig. 5, the space heating reduction data of the different ESM applied to the whole district are presented in Table 6, as well as the peak load to be met by the ESS (L_{LT}^{PEAK}). For the latter, a centralisation factor of 0.8 was assumed, as suggested in design guides of district heating projects (Institut Catalá d'Energia, 2012).

Table 7
Investment required for implementing the proposed grid.

	Measurements (m)	*Unit cost (€/m)*	*Total investment (€)*
Piping (including insulation and accessories)	12,604	46	579,784
Civil works	6,302	94	592,388
TOTAL			1,172,172

Table 8
Variable costs under consideration.

Fuel	Unitary cost (€/kWh)
Natural gas - C_{NG}^{MAN}	0.054
Biomass (Pellet) - C_{BIO}^{MAN}	0.041
Electricity (purchase) - C_{ELE}^{BUY}	0.223
Heat (sale) - $C_{HT}^{SELL}, C_{MT}^{SELL}, C_{LT}^{SELL}$	0.000
Electricity (sale) - C_{ELE}^{SELL}	0.0496

3.3. Energy supply systems

As the intervention is focused at full district level, a district heating network was considered for all the cases as the infrastructure for space heating and DHW transport. The presented methodology allows including several alternatives for the district network topology, so the optimal configuration would be a result of the optimization problem. However, in this case study, the district heating network was optimized in advance, being the topology common to all the ESS alternatives. Specifically, the district heating network considered here encompasses an external ring that encloses the district through its external perimeter, and some radial grids, which divide it in "sub-rings" (Fig. 6). The main pros of this typology are that i) it allows supplying every building; ii) it is more flexible when different maintenance works are carried out in different parts of the grid; iii) it allows the possibility of building the grid in different phases, reducing the time for starting operating and (iv) it makes the hydraulic pressure balance easier. Based on this layout, the costs for this alternative are presented in Table 7.

Besides these costs, it should be also considered the cost of the building where the thermal production is located. However, this cost is variable depending on its location, architectural design and civil works requirements. It should be noted that this cost was not considered in this study, neither the costs related to the connexion of the buildings of the district to the thermal grid.

Table 9
ESS technologies (Iturriaga et al., 2018).

Technology	Efficiency	Specific cost	Module
Compound parabolic collector	$\eta_0 = 64.5$ %; $k_1 = 0.858$; $k_2 0.005$	$c = 2,900.8\ n^{-0.211}$ (€/u)	HT
Organic Rankine CHP	$0.8517\ P_e^{0.0112}$ (thermal) $0.0675\ P_e^{0.0177}$ (electricity)	$c = 32,617\ P_e^{-0.503}$ (€/kWe)	HT
Thermal Energy Storage	–	$c = 63.353\ V^{0.646}$ (€/L)	HT, MT, LT
Evacuated tube collector[a]	$\eta_0 = 79.6$ %; $k_1 = 1.282$; $k_2 = 0.008$	$c = 3,169.4\ n^{-0.176}$ (€/u)	MT
Internal Combustion Engine CHP	$0.7805\ P_e^{-0.039}$ (thermal) $0.2042\ P_e^{0.1367}$ (electricity)	$c = 12,480\ P_e^{-0.548}$ (€/kWe)	MT
Gas Turbine CHP	$0.7754\ P_e^{-0.131}$ (thermal) $0.1551\ P_e^{0.129}$ (electricity)	$c = 7,900.2\ P_e^{-0.397}$ (€/kWe)	MT
Biomass boiler	$0.9391\ P_t^{-0.006}$	$c = 1,584.4\ P_t^{-0.305}$ (€/kWth)	MT
Conventional natural gas boiler	$0.9833\ P_t^{-0.002}$	$c = 1,243.2\ P_t^{-0.415}$ (€/kWth)	MT
Flat plate collectors[a]	$\eta_0 = 79.2$ %; $k_1 = 3.666$; $k_2 = 0.013$	$c = 2,574.7\ n^{-0.302}$ (€/u)	LT
Condensing natural gas boiler	$1.0492\ P_t^{0.0021}$	$c = 1,589.7\ P_t^{-0.475}$ (€/kWth)	LT
Air-to-water heat pump	$3.7035\ P_t^{-0.026}$	$c = 381.99\ P_t^{-0.144}$ (€/kWth)	LT
Amorphous photovoltaic modules[b]	$\eta_0 = 7.83$ %; $\gamma = -0.19$ %/°C	$c = 553.48\ n^{-0.205}$ (€/u)	Electricity
Mono & Polycrystalline photovoltaic modules[b]	$\eta_0 = 15.3$ %; $\gamma = -0.40$ %/°C	$c = 719.34\ n^{-0.042}$ (€/u)	Electricity

[a] The solar thermal collector efficiency is given by $\eta = \eta_0 - \frac{k_1 \cdot (T_m - T_{amb})}{G} - \frac{k_2 \cdot (T_m - T_{amb})^2}{G}$ (Ministerio de Vivienda, 2013).
[b] The photovoltaic collector efficiency is given by $\eta = \eta_0 \cdot \{1 + \gamma \cdot (T_C - T_{REF})\}$ (EVE (Ente Vasco de la Energía - Basque Energy Agency), 2013).

Regarding the electricity, the low-tension distribution network is used to provide the electricity needs, as well as absorb the electricity exports. The variable costs associated to the purchase and sale of energy are presented in Table 8.

Regarding energy systems under consideration, the set of technologies listed in Table 9 were considered as eligible options for the design of the ESS. Annual maintenance and operating costs were included as 2.5 % of the plant cost, while a discount factor of 2.5 % per year and a lifetime of 20 years were considered for energy supply system technologies. It was considered that all the technologies can regulate their load capacity from 0 to 100 %, except CHP units, which can only regulate from 60 % to 100 %. As far as Primary Energy Weighting factors are concerned, the official values provided by the Spanish government have been used, i.e. 2.368 for electricity, 1.195 for natural gas and 1.113 for Biomass (Ministerio de Industria, 2014). Finally, although some external parameters could vary, the marginal effects of such exogenous uncertainties were evaluated in detail by a sensitivity analysis presented in (Iturriaga et al., 2018), and it was observed that there was no significant variability in the results.

4. Results and discussion

The optimisation method was applied to the case study in order to obtain the optimal ESM in combination with the optimal design and operation of the ESS. While the nZEB definition by State Members usually do not consider the individual electricity consumption of the inhabitants, we believe that this is essential for a true definition of nZEB buildings and by extension, Zero Energy Districts. Taking this into account, three different cases are defined in relation to the NRPE consumption of the district.

i) Cost-optimal solution: Renovation option that offers the lowest annual cost without any restriction to its NRPE consumption.
ii) ZED: Renovation option that offers the lowest annual cost meeting the Zero Energy District condition ($NRPE = 0$)
iii) ZED': Renovation option that offers the lowest annual cost meeting the Zero Energy District condition including the domestic electricity consumption of the district. In this case, an alternative NRPE is defined as follows: $NRPE' = NRPE - \overline{L}_{ELE}^{DEB} \cdot W_{ELE} = 0$.

Table 10 presents the optimal configuration for the ESM and ESS for the 3 cases.

Regarding envelopes, for both the optimal case and ZED case, the "improved scenario" was selected, i.e. to increase the insulation up to 8 cm in façades and 14 cm in the case of roofs. However, for the ZED' case, no improvement is selected for the envelopes of the buildings. In the three cases, the original windows are maintained. As far as ESS technologies are concerned, cogeneration by means of internal combustion engines is included in the three cases, together with the medium temperature thermal energy storage systems, and condensing natural gas boilers.

In the ZED' case no ESM is taken, being higher the peak thermal load, which results in a higher power for both internal combustion engines. Related to this, a higher CHP power requires a higher storage capacity in order to couple a higher thermal production with higher loads. Even though the selection for this case could result contradictory at first sight, this is explained by the effect that internal combustion engine- based CHP has on the NRPE consumption. As electricity efficiency of the internal combustion engine is higher than the primary energy-weighting factor for electricity, exported electricity is accounted as a negative NRPE consumption. Therefore, since heat and electricity production of

Table 10
Configuration of the optimal ESS and ESM designs at district scale.

		Module	ZED' (NRPE' = 0)	ZED (NRPE = 0)	Optimal Cost
ESS technology	Compound parabolic collector	HT	–	–	–
	Organic Rankine CHP	HT	–	–	–
	HT Thermal Energy Storage	HT	–	–	–
	Evacuated tube collector	MT	–	–	–
	Internal Combustion Engine CHP	MT	3000 kW_e	1500 kW_e	1500 kW_e
	Gas Turbine CHP	MT	–	–	–
	Biomass boiler	MT		–	1500 kW_e
	Conventional natural gas boiler	MT	–	500 kW	–
	MT Thermal Energy Storage	MT	20,000 l	40,000 l	40,000l
	Flat plate collectors	LT	–	–	–
	Condensing natural gas boiler	LT	6000 kW	5000 kW [1]	2500 kW [1]
	Air-to-water heat pump	LT	–	–	–
	LT Thermal Energy Storage	LT	–	–	–
	Mono & Polycrystalline PV modules	Electricity	–	–	–
			CASE 0	CASE 2	CASE 2
ESM	Wall insulation		2 cm (U = 0.74 W/m^2 K)	8 cm (U = 0.36 W/m^2 K)	8 cm (U = 0.36 W/m^2 K)
	Roof insulation		–	14 cm (U = 0.26 W/m^2 K)	14 cm (U = 0.26 W/m^2 K)
	Windows		4 / 6 / 4 [2] (U = 4.12 W/m^2 K)	4 / 6 / 4 [2] (U = 4.12 W/m^2 K)	4 / 6 / 4 [2] (U = 4.12 W/m^2 K)

[1] Only for covering peak periods, do not run under reference days.
[2] This solution corresponds to the current windows.

Table 11
Operation results for the three analysed cases.

		ZED' (NRPE' = 0)	ZED (NRPE = 0)	Optimal Cost
NRPE	NRPE (kWh/m^2 y)	−91.1	0	−22.6
	NRPE' (kWh/m^2 y)	0	91.1	68.5
Thermal Energy	Thermal energy load (kWh/y)	13,496,570	10,881,514	10,881,514
	CHP IC engine (kWh/y)	28,700,973	7,672,981	8,155,522
	Conventional boiler (kWh/y)	0	4,434,694	0
	Condensing boiler (kWh/y)	30,920	0	0
	Biomass boiler (kWh/y)	0	0	3,730,691
	Stored energy (kWh/y)	473,768	646,496	1,216,195
	Heat release (kWh/y)	15,235,323	1,296,162	1,074,700
Electricity	Electricity load (kWh/y)	6,567,013	6,567,013	6,567,013
	Electricity generated (kWh/y)	25,281,897	6,577,650	7,056,406
	CHP IC engine (kWh/y)	25,281,897	6,577650	7,056,406
	CHP PES (%)	23.7	34.8	36.1
	PV panels (kWh/y)	–	–	–
	Exported electricity (kWh/y)	18,714,884	12,569	489,394
	Self-consumed electricity (kWh/y)	6,567,013	6,565,081	6,567,013
	Imported electricity (kWh/y)	0	1,933	0

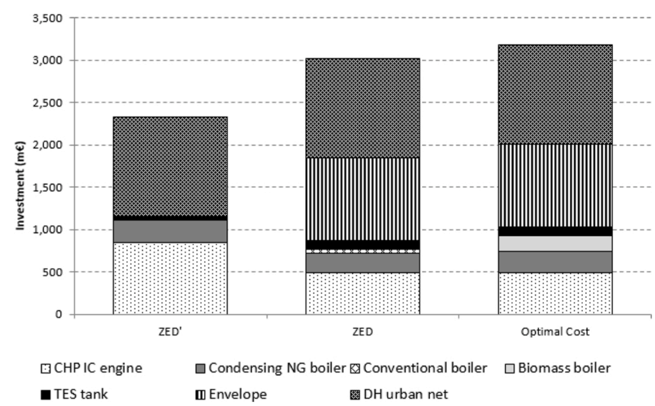

Fig. 7. Initial investment in each case.

the CHP unit are linked,

a higher thermal load (useful heat demand) justifies a higher electricity production and therefore, a higher electricity export, which means a reduction of the NRPE consumption. This is a common fault when the nZEB is defined and emphasizes the need for not only limiting the NRPE consumption, but also the thermal loads, as well as the total Primary Energy consumption. Learning from this, in Spain, the last update of the Spanish Building Code includes a limit for the total Primary Energy consumption in the definition of nZEB buildings, which will come into effect in July 2020 (Ministerio de Vivienda, 2013). Presumably, this would lead to the PV production substituting the current production by CHP.

Apart from the basic configuration of internal combustion engine, medium temperature thermal energy storage systems and condensing natural gas boilers, the ZED case includes a conventional natural gas boiler of 500 kW and the Optimal Cost, a biomass boiler of 1500 kW. It should be noticed, that the optimization is constrained to meet the design peak load, although some thermal production units works at a very limited number of hours. This is better understood from the analysis of Table 11, which summarises the actual operation of the different ESS considered for the three cases.

The thermal energy load varies for each depending on the ESMs selection. Therefore, this load is higher for the case of ZED' since no improvement was selected for the building's envelope. It can be seen that the heat load is mainly met by internal combustion engines for all the 3 cases, while the other technologies are mainly used for meeting the peak power. Specifically, in the Optimal Cost and ZED cases, condensing boilers were installed in order to meet the peak load constraint (Eq. 8), although they do not operate under nominal operational conditions. Condensing boilers were selected in this case, as they offer the lowest cost for the installed thermal power at that range of thermal powers (see specific cost column in Table 9). In all the cases, the non-CHP thermal production is only used to meet the load during those moments when the

Table 12
Economic results for the three analysed cases.

	ZEB' (NRPE' = 0)	ZEB (NRPE = 0)	Cost Optimal
Investment (€)	2,238,543	3,022,275	3,133,206
Variable costs (€/y)	1,360,112	755,960	731,500
Annual cost (€/y)	1,476,539	907,074	888,161
Annual savings (€/y)	396,496	1,000,647	1,025,107
Payback (y)	1.67	1.35	1.43

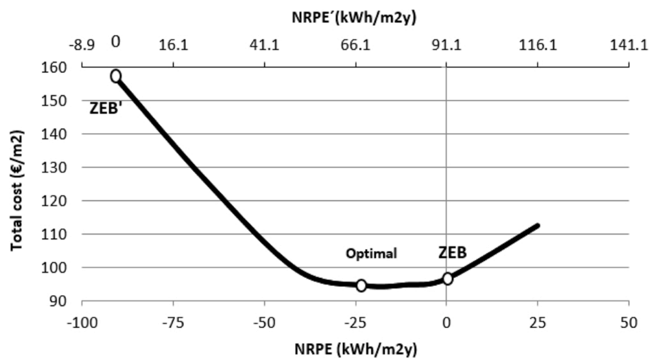

Fig. 8. Minimum annual cost for the different values of NRPE.

CHP plus the thermal energy storage cannot meet the load, either because this is too high or too low, i.e. the CHP cannot operate below 60 % of its nominal power.

Electricity demand is exclusively supplied by the internal combustion engines, except for the case of ZED, which in some specific moments electricity is imported from the grid. In general, for all the cases, the internal combustion engine CHP acts as a power plant that covers the needs of the district, exporting the energy surplus. The effect of the exported electricity in reducing the NRPE consumption makes it, under the specific constraints in this analysis, preferable to renewable electricity production by PV technology. As it was stated, this would be affected by a legislation that limits the gross primary energy consumption.

As far as economic analysis is concerned, the capital investment for each case is presented in Fig. 7. The shares of the investment corresponding to each ESS technology, ESM and district network are depicted in it.

Thus, the highest impact on the investment is that related to the district network, followed by the investment for improving the envelope (ESMs), due to the large envelope area to be renovated (façades and roof areas). Regarding the ESS technologies, the internal combustion engines for CHP present the most important economic effect.

The economic analysis has been carried out by comparing the investment against the obtained economic savings. Simple payback method has been used to carry out the feasibility analysis. The main economic results are presented in Table 12.

Variable costs correspond to electricity and fuel costs required for operating the systems, as well as maintenance costs. Annual cost includes, on a yearly basis, the variable costs plus the yearly amortisation, both for ESS technologies and for ESMs, as well as for the district network. Annual savings have been calculated using as a reference case based on a 9000 kW system based on natural gas boilers for supplying the thermal energy demand of the current situation (with no renovation of the envelope), being the electricity demand fully imported from the grid. This reference case involves an initial investment of 1,667,220 € including the cost related to the heating district network, and yearly variable costs of 1,756,608 €/year.

Solving parametrically the optimisation problem for intermediate cases allows to get the cost-optimal curve presented in Fig. 8. In it, the three obtained cases (ZED', optimal cost and ZED) have been remarked.

It should be noted that the method is an optimization that only offers the configuration and its operation that minimizes the annual cost for each level of NRPE. This way, the curve depicted in mentioned figure is an approximation obtained by discretizing several NRPE consumption limits.

For the district evaluated in this paper, the Optimal-Cost case (considering the lifespan of 20 years assumed for EES technologies) is achieved when the limit required for non-renewable primary energy when the electricity consumption is omitted (NRPE') is −22.6 kW h/m^2, or 68.5 kW h/m^2 when it is included (NRPE). However, when the simple payback is evaluated, the lowest value is obtained in the ZED case, as shown in Table 12. It is explained since the initial investment for the optimal cost is higher, being the annual savings similar in both cases. It should be noted that the obtained payback periods are significantly low, due to the fact that the initial investment related to the construction of the building for the thermal plant and other related issues have not been taken into consideration. These costs would not be applicable to the reference case, so in the event of considering them, the resulted payback periods would be longer.

5. Conclusions

In previous research, the authors developed a method for the optimal energy design of buildings, covering both ESSs and ESMs (Iturriaga et al., 2017, 2018). In this work, that method has been upgraded to enable its applicability to the energy retrofitting of entire districts connected to district heating networks. Thus, from a limit set of data by the user, it is possible to get an energy-retrofitting plan to meet certain energy performance objectives at the lowest annual cost. One of the main challenges, due to the high casuistry of building typologies, is the characterization of the thermal demand of the district. For that aim, the concept of District Equivalent Building was included, this being a virtual building with energy loads of the full district under consideration. A general methodology is proposed, which allows getting the District Equivalent Building from an inventory of the district. The methodology was conceived to be applied with GIS tools, enabling the clustering of the buildings under certain pre-set categories. These building clusters are analysed in detail by dynamic energy simulation to get the full definition of the District Equivalent Building, which can be used as an input for the optimization methodology.

This approach is applied to the residential district of Otxarkoaga, located in Bilbao (northern Spain). Considering the action at district scale, a district heating network is considered as the basis for the future energy system. The method allows getting the optimal energy retrofitting plan required to get certain energy performance objectives, defined by the non-renewable primary energy consumption of the district. From the results of the optimization under the different scenarios, it is get that district heating network results in an efficient and feasible solution for the energy supply of the district. Due to the current constraints by the Spanish legislation, the resulting configuration resulted, for all the considered scenarios, a CHP power plant meeting the needs of the district, exporting the surplus electricity to the distribution networks. Limitations on the gross primary energy consumption of the building will limit this solution, promoting the installation of distributed renewable technologies, such as PV panels.

To conclude, the method results into a very suitable tool for the preliminary study of district heating networks. Due to its simple nature, it is mainly conceived to be used as a rule-of-thumb design at initial design stages, while more detailed analysis should be necessary at more advances stages of development: specific design of the heating network, definition of the specific actions for the interconnection of the buildings to the network, etc. For the moment, the demand determination is made by dynamic simulation, which somehow reduces the applicability of the method. As part of the future works, a simple method for the specific demand estimation of the building clusters would help to increase the applicability of the method, reducing the need for work by the user. As far as future steps for improving the deterministic MILP model of the District Equivalent Building is concerned, it is planned to include both exogenous and endogenous sources of uncertainty by extending the model to a two-stage stochastic optimization problem with decision dependent probabilities (see in Hellemo et al. Hellemo, Barton, and Tomasgard (2018) a taxonomy and literature review for stochastic programs with decision-dependent uncertainty). Particularly in this approach, user behaviour randomness is decision-dependent, i.e. the selected ESM and ESS affect the load curves variability, therefore is endogenous. On the other hand, investment and energy costs uncertainty are exogenous.

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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