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Difficulties in the energy renovation processes of district heating buildings. Two case studies in a temperate climate

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A R T I C L E I N F O

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A B S T R A C T

Renovation at district scale is a key strategy to reduce CO_2 emissions and energy consumptions by optimising the implementation of renewable energy sources and taking advantage of economies of scale. In this context, this paper focuses on assessing the positive impacts and difficulties after the energy rehabilitation of thermal envelopes in two buildings that belong to two different District Heating systems. The methodology is based on the comparative analysis of indoor temperatures data and energy consumption data of 17 monitored dwellings. The results showed a significant association between the improvement of envelopes and the increase of indoor temperatures in winter (β=0,644). Due to some technical and social barriers, the heating system was not regulated after the rehabilitation, so energy consumption was unnecessarily high, there were situations of indoor overheating in winter (maximum average indoor temperatures between 24-26°C) and these issues produced dissatisfaction on neighbours. In order to avoid these negative consequences, some recommendations are provided, such as informing neighbours about expectations in each step of the long rehabilitation process, reconsidering payments to promote the envelope rehabilitation but maintaining a fixed cost to protect vulnerable groups, and promoting post-occupational studies that contribute to the viability and up-date of this kind of District Heating systems.

1. Introduction

To achieve a low-carbon economy and low carbon cities in 2050, it is essential to take into account building stock since it involves 40 % of the world's total energy use and 30 % of CO2-emissions (Statistical Office of the European Union, 2011).

In this way, a lot of countries have had a strong focus on the energy efficiency of new buildings during the last few decades. However, the building stock is relatively old and the replacement rate is low: for example, in Spain –where this study is developed– it is estimated by the INE (Spanish Statistics National Institute, s. f.) that 70% of the housing stock to be used in 2050 has already been built and between 63% and 76% of the existing housing stock was built before the first energy demand regulations of buildings NBE CT-79, (Ministry of Public Works and Urban Development. Spanish Government 1979).

Therefore, the energy rehabilitation of buildings is essential, and in order to guide these processes, the European policy framework aims to create the conditions and guidelines for improving the energy efficiency of existing and new buildings (D'Agostino et al., 2017). Research analysing the energy efficiency and renovation of buildings is typically focused on single buildings (Almeida & Ferreira, 2017; Domingo-Irigoyen et al., 2015; Mørck et al., 2016). However, due to the increasing

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complexity of the infrastructure regarding generation, distribution and use of energy, the single building perspective can lead to sub-optimization for the community or society as a whole (Reynolds et al., 2017). Furthermore, focussing on entire neighbourhoods could be beneficial through economies of scale, higher levels of efficiency in relation to use of resources, minimization of waste (Paiho et al., 2015) and the greater potential they have for implementing renewable energies (Zajacs & Borodiņecs, 2019).

Nevertheless, systems as complex and large as District Heating (DH) involve long rehabilitation processes in which barriers and challenges can appear. Because of that communities of neighbours cannot want to carry out this type of process. In particular, some social groups (those with low-income, renters, or the elderly) experience more barriers for undertaking a building retrofitting due to factors such as upfront costs, "presentism" thinking, split incentives, disruption and lack of control (Camprubí et al., 2016).

In order to achieve efficient rehabilitation, research about these complex processes is essential: studies that contrast the previous state of the building with the rehabilitated one allow to quantify the improvement of indoor environmental conditions, the reduction of energy consumption and CO_2 emissions, and to analyse those measures or strategies that were successful and others that can be improved in future interventions. In this way, it will be possible to better analyse the steps of different processes, in order to refurbish and regenerate these DH more cost-optimally and go to low emission and low energy districts (EBC, s. f.).

District heating retrofits are usually studied by analysing the final benefits of these interventions, such as the reduction of CO_2 emissions and energy savings, the improvement of inhabitants' comfort conditions and the increase of the economic value of buildings (Andrić et al., 2018; Domingo-Irigoyen et al., 2015; Gustafsson et al., 2016; Paiho et al., 2015). In this context, complementary to previous research and based in two Case Studies, this paper is focused on detecting the barriers that may appear during the rehabilitation process and provides some recommendations to overcome them in order to guarantee a successful end of the rehabilitation.

This paper presents two Case Studies to assess District Heating Energy Renovation Processes after the rehabilitation of the envelopes.

The specific research objectives of this paper are:

- To analyse the main positive impacts and difficulties between envelopes' non-rehabilitated scenario (nR) and envelopes' rehabilitated scenario (R).
- To propose some recommendations to face the long processes of energy rehabilitation of a DH.

The paper is organized as follows: After the Introduction section, the Case Studies and data collection methodology is presented in Section 2: 2.1 contains a description of case studies, the climate where they are placed and the rehabilitation process in which they are involved and 2.2 contains the description of data analysis; The results of monitoring campaigns are showed in Section 3; Finally, the results and recommendations for DH rehabilitation processes are discussed in Section 4 and conclusions in Section 5.

2. Methodology

The methodology carried out includes the study of the energy rehabilitation project and the analysis of the situation after completing the rehabilitation process of the envelopes.

2.1. Case studies description

The selected case studies are located in Pamplona, a city in the North of Spain. Both buildings were built in 1971, that is, before the first Spanish regulation on energy saving NBE-CTE-79 (Ministry of Public Works and Urban Development. Spanish Government 1979) so they were built without insulation in the thermal envelope (see envelopes' original characteristics in Table 1). They were selected because both belong to two different District Heating and are representative of two residential block typologies of this period in Spain: linear block (S1) and high-rise building (T2). Both buildings were rehabilitated within the context of the *Efidistrict Fwd* project promoted by the Government of Navarra and the public housing company, NASUVINSA (*Efidistrict Fwd*, s. f.).

Although the neighbour's profile is varied, almost half of them are people over 65 years old and retired, with one or two persons per dwelling. Almost 50% of them are the first generation of people who lived in these buildings built in the 1970 and dwellings are all privately owned.

2.2. Climate

Pamplona has a Cfb climate (according to Koppen-Geiger classification), temperate without dry season, "oceanic" type. Following data from the 1980-2010 climate series of the Spanish State Meteorological Agency (AEMET AEMET. (s. f.) 2017) the average annual temperature is 12.7°C: January is the coldest month with a monthly average of 5.2°C and a monthly average minimum of 1.4°C, and August is the warmest month. According to the same climatic series, the annual average relative humidity is 67%: December and January are the wettest months (with a monthly average of 78% RH) and July and August are the driest months.

2.3. Typology and distribution

Case study S1 is a building in linear typology between two blocks and with 5 floors (Ground floor+4). It is configured with 2 dwellings per floor with double orientation (8 dwellings in total per block), and commercial areas on the ground floor. The main orientation is Northwest (NW) and the secondary orientation to a semi-opened courtyard is Southeast (SE). The heated area of each dwelling is 70.10 m^2 and its layout consists of kitchen (K), living room (LR), bathroom (T), three bedrooms (BR) and a balcony (B) (Fig. 1).

Case study T2 is a high-rise building with 10 floors (Ground floor+9). It is configured with 4 dwellings per floor (36 dwellings in total per block) and commercial areas on the ground floor. The main orientations of the rooms are Northwest (NO) or Southeast (SE), depending on the dwelling, one of them facing a small semi-opened courtyard. The heated area of each dwelling is 67.18 m^2 and its program consists of kitchen (K), living room (LR), bathroom (T), three bedrooms (BR) and a balcony (B) (Fig. 2).

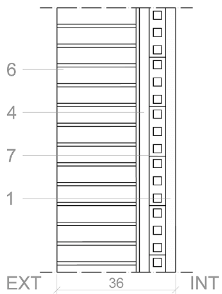
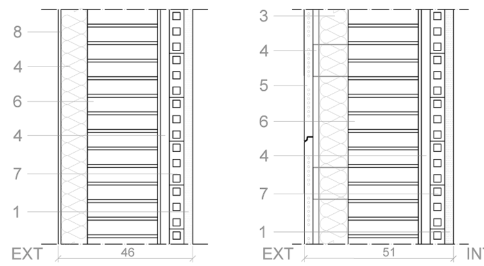
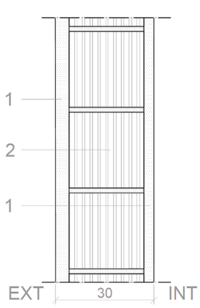
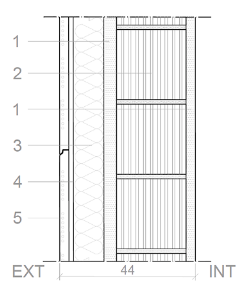
2.4. District Heating's' characteristics

Both case studies are located in the same social neighbourhood, called "La Chantrea", in Pamplona (Fig. 3), but are part of two different District Heating (DH). Both DH were created as cooperatives, so all the neighbours are owners of the system.

S1 is part of the "*Santesteban*" DH, which comprises 366 dwellings. The heat source of this DH is a standard natural gas boiler with a nominal heat power of 3.488kW. The distribution network starts in the boiler room and reaches each block of DH. Interior heating distribution in S1 consists of a two-pipe columns system per radiator (Fig. 4. A). This interior distribution does not allow placing individual thermostatic valves (metering / regulation) per dwelling but permits their installation per block and per radiator. The system allows to dwellings to disconnect from the DH in favour of individual systems.

T2 belongs to the DH called "*Orvina II*" which comprises 1.200 dwellings belonging to 38 high-rise buildings. The heat source of this DH are two standard natural gas boilers with a nominal heat power of 5.800kW each. The distribution network starts in the boiler room and

Table 1
Thermal envelope characteristics of study cases: non-rehabilitated (nR) and rehabilitated (R).

	nR	R
S1		**FAÇADES**
	  *U=2.21 W/m2 K*	 Northwest façade (NW): A ventilated facade system is added to the original one. Southeast façade (SE): An ETICS system is added to the original one.  *U_{NW}=0.27 W/m2 K U_{SE}=0.29 W/m2 K*
		ROOF
	Pitched roof with ceramic tiles and without thermal insulation.	12cm of mineral wool insulation was added over the horizontal slab and 4cm of XPS under the tiles. (16 cm of thermal insulation in total). *U= 0.27 W/m^2 K*
		WINDOWS
	Wooden frame with single glazing Shading: wooden roller blinds	PVC monoblock system with thermal break. U= 1.6W/m^2 K. Double glazing with argon air cavity. U= 1 W/m^2 K; g=0.41.
T2		**FAÇADES**
	 FAÇADES  *U=1.15 W/m2 K*	 Ventilated facade system is added to the original one.  *U=0.25 W/m2 K*
		ROOF
	Flat roof with gravel cover and 3cm XPS.	Flat roof with gravel cover and 8cm of insulation over the existed one (11cm of thermal insulation in total). *U=0.31 W/m^2 K*
		WINDOWS
	Wooden frame with single glazing. Shading: wooden roller blinds Some neighbours had renovated them for new ones.	Only windows that did not comply with CTE were replaced. The transmittance was estimated: *U=2.70 W/m^{2}K* for the older ones and *U=1.13 W/m^{2}K* for those replaced in the rehabilitation.

Note: 1. Plaster (3cm); 2. Prefabricated concrete blocks lightened with ceramic elements (23cm); 3. Mineral wool insulation (10cm); 4. Air cavity (5cm); 5. Ceramic cladding; 6. Solid brick (24 cm); 7. Brick (5 cm); 8. Plaster (1cm)

reaches high-rise building of DH. Interior heating distribution in T2 consists of one-pipe columns system per radiator (Fig. 4. B). This interior distribution does not allow the regulation of temperatures or the installation of thermostatic valves (metering / regulation) either per dwelling or per radiator but allows their installation per group of high-rise buildings. This "waterfall" distribution involves that regulating or closing a radiator in a dwelling would leave the upper dwellings without heating. Because of that, this DH does not allow to shift any dwelling to an individual heating system.

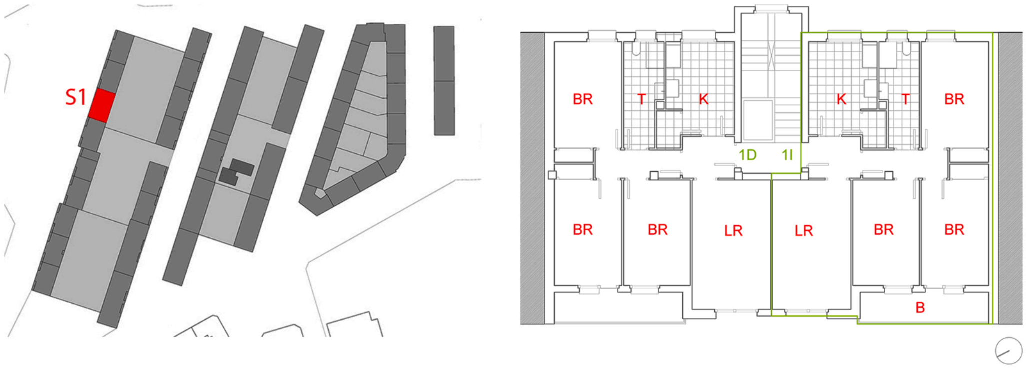


Fig. 1. S1: District Heating plan and dwelling plan

Fig. 2. T2: District Heating plan and dwelling plan

2.5. Neighbour Rehabilitation Project

In addition, both DH have been included in the project “Calor Txantrea” Distict Heating (Ain, 2018). This project that began in 2020 consists of an urban regeneration plan for the entire social neighbourhood that proposes to unify the 9 existing DH in the neighbourhood in a unique District Heating.

According to the project, this new DH will provide heating for 4,751 dwellings (414,650 m2 of heated area) from a single heating plant (heat source from 2 biomass boilers with a total power of 9 MW). The rehabilitation process aims to mobilise an estimated total investment of 11 million euros in three main energy efficiency steps: *Step 1*) Thermal envelopes' rehabilitation of those buildings built between 1950-80; *Step 2*) Creation of a new heating plant and new distribution network to be supplied with biomass; and *Step 3*) Renovation of the old urban network and the buildings' distribution systems to incorporate regulation and control systems.

No improvements in the ventilation system or the installation of heat recovery systems are considered in the refurbishment.

These actions are expected to achieve positive economic, social and environmental impacts: a total energy savings of 6294 MWh/year, 3993 TCO_2 emissions savings of GHG-CO_2, a renewable energy production of 14756MWh/year and a generation of 174 jobs related to the green economy (Ain, 2018).

Until the moment of this research, only Step 1 (Buildings Thermal Envelopes' Rehabilitation) has been carried out in S1 and T2. Their envelopes were rehabilitated in 2018 following the Spanish Building Code CTE-HE 2017 (Development, 2019), looking for standards close to nZEB in its energy demand (see envelopes' characteristics after the refurbishment in Table 1). The heating system (urban networks, interior distribution and heating source) after this step is still the same.

2.6. Data analysis

The data used for this analysis has been obtained in 4 monitoring campaigns: 2 before the rehabilitation (nR) and 2 after the rehabilitation (R) scenarios (Table 2). Representative dwellings have been selected in both buildings, with data-loggers placed in dwellings in the first floor, intermediate floor and top floor. During the time that sensors were installed in the dwellings, ten-minute data of temperature and relative humidity were collected in living room and bedroom, generally located in opposite orientations. The data-loggers were MAGDETECH (accuracy in temperature of $\pm$ 0.5°C and in relative humidity of $\pm$3%).

The data analysis involves comparative multiple regression (ie.” ordinary least squares”, OLD) considering the following variables:

- Dependent variables: indoor temperatures (before and after envelopes' rehabilitation) were considered. Each value included in this analysis (N=90) corresponds, for each dwelling, to the average ten-minute data of indoor temperature with the same hourly average outdoor temperature.
- Independent variables: envelopes' type (nR-R), dwellings' height position and the average outdoor temperature corresponding to each of the observations made were considered.

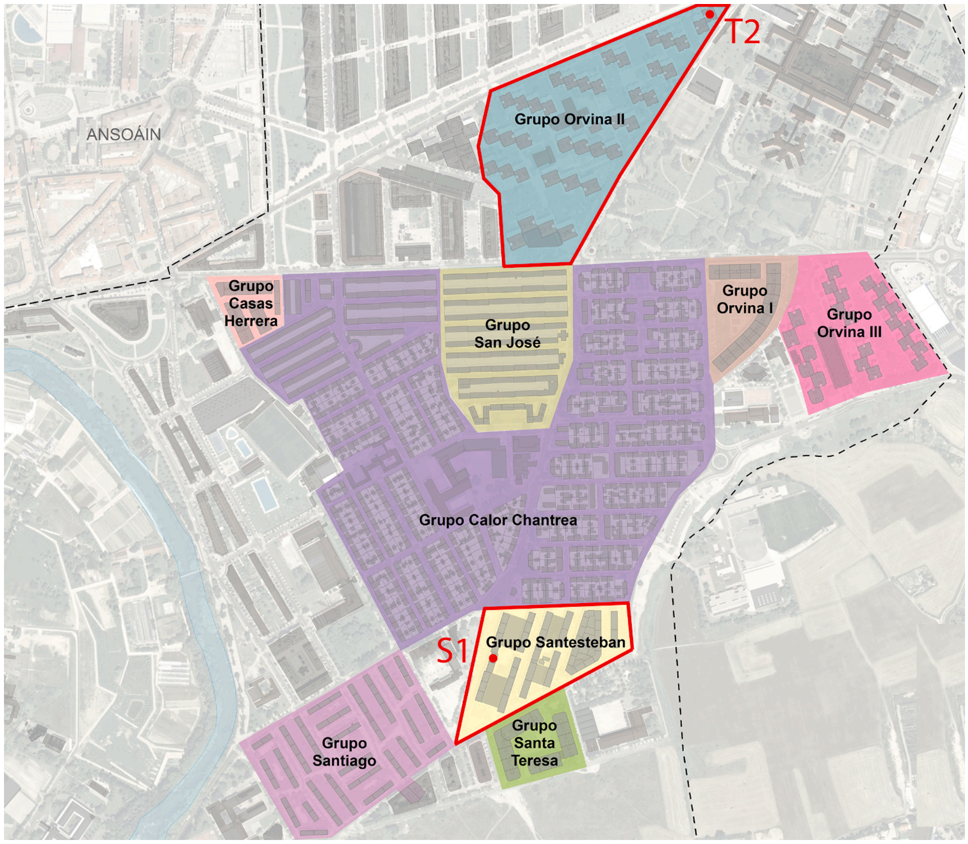


Fig. 3. District heating in “la Chantrea” neighbourhood (9 DH) and the location of the case studies S1 and T2.

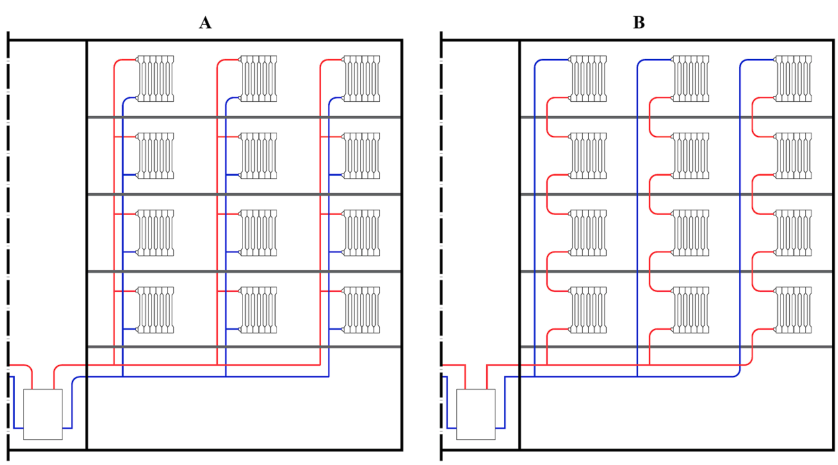


Fig. 4. A: Heating system distribution in S1; B: Heating system distribution in T2

Table 2
Summary of the 4 monitoring campaigns carried out in buildings S1 and T2: non-rehabilitated (nR) and rehabilitated buildings (R), in winter conditions.

BLOCK	CODE	WINTER
S1 (TOTAL: 8 dw)	nR	26/03/2014 - 02/04/2014 1 dwelling monitored
	R	12/02/2018 - 01/03/2018 5 dwelling monitored
T2 (TOTAL:36 dw)	nR	19/02/2015 - 04/03/2015 4 dwelling monitored
	R	23/11/2018 - 24/01/2019 7 dwelling monitored

Ten-minute graphs of indoor temperatures and humidity (for R scenario) and indoor temperatures' frequencies (for R scenario) analysis have been carried out. For the analysis of indoor temperature after the rehabilitation, the recommended temperature of UNE EN 16798-1 (CNT100-CLIMATIZACIÓN, 2020) for a Category II of indoor environment in mechanically heated buildings (medium level of expectation, usually applied on renovated or new building) is 20°C. This limit is the minimum recommended for the elderly and very young children due to their sedentary lifestyle and their thermoregulatory system (Jevons et al., 2016). The World Health Organization (WHO) (World Health Organization, 1987) (Howden-Chapman et al., 2017) recommends other limits for winter conditions (18-24°C) and they were also considered. In addition, the recommended range for indoor relative humidity is also indicated (with the accepted minimum of 30%, from the point of view of people's well-being and energy saving, according to Spanish standards, RITE (IDAE, 2013).

Moreover, energy consumption per heating season is compared between nR and R scenarios in relation with Heating Degree Days (HDD).

3. Results

3.1. Indoor temperatures comparison before and after the envelope's rehabilitation

The developed regression model is summarised in Table 3. It shows that the improvement of the buildings envelopes characteristics (R) is significantly associated with an increase of indoor temperatures in winter (β=0,644). This increase in temperatures after refurbishment is greater in first and last floors of the buildings (Fig. 5).

Thermal oscillations continue being high after rehabilitation due to the pattern of natural ventilation, used by the majority of dwellers to "regulate" temperatures: in S1 (average oscillations between 3 - 8°C) and less pronounced in T2 (average oscillations between 2 - 5°C). However, the refurbishment favours higher indoor temperatures in colder periods with respect to the non-rehabilitated situation (Fig. 5).

3.2. Indoor temperatures and relative humidity after the rehabilitation

The coldest weeks of the monitoring campaigns (see Table 2) are selected to show the results after rehabilitation. The heating schedule of the district heating is shaded in grey (12:00-22:00 h in both blocks).

After renovation (see Fig. 6 for S1 and Fig. 7 for T2), during heating hours, maximum average temperatures are between 24-26°C (dwelling 1D of S1 even reaches 30°C, when the outside temperature is around 2°C at that time). The minimum temperatures have risen with respect to the previous situation, always being above 20°C both in S1 and T2. Only one dwelling in S1 dropped under 20°C, due to the excessive use of natural ventilation to reduce high temperatures.

Because of high temperatures reached by radiators, relative humidity has decreased and it is between 30-40%, and even below 25% punctually.

Fig. 8 shows a summary of the indoor temperature frequencies per dwelling. All dwellings in both buildings have a high percentage of hours outside adequate ranges in overheating situations in winter. This is especially pronounced in living rooms: all of them are approximately 50% of the time above 24°C and some of them even more than 75% (see dwelling 4D in S1 and dwellings 9A and 9C in T2).

3.3. Energy consumption

The annual consumptions (from October to May, both included) before and after the renovation for S1 are included in Table 4 and for T2 in Table 5.

In S1, there is no reduction in consumption after the envelopes' rehabilitation. Even in 2019, the consumption is higher. This was due to a failure in the supply temperature setpoint. In T2, in the first winter campaign after rehabilitation, consumption was almost the same as before. However, in winter 2019-20, heating temperature was regulated (by lowering the setpoint temperature 2°C), resulting in energy savings of 16% per dwelling (compared to winter 2017-2018). Even so, the energy certification standards foreseen in the project were not achieved.

For both case studies, the payments are monthly, fixed and equal every month of the year per dwelling, and have not changed after the rehabilitation: 60 €/month per dwelling in S1 and 90 €/month per dwelling in T2.

4. Discussion

The main positive impacts of the envelopeś rehabilitation are that minimum indoor temperatures in the dwellings are guaranteed in both case studies during the winter campaign and that favours higher indoor temperatures in cold periods with respect to the non-rehabilitated situation (see section 3.1). However, some difficulties have also been detected after completing the first step of the DH energy rehabilitation process: the first one is that all rehabilitated dwellings present overheating when the heating systems are working (see section 3.2) and the second one is the unnecessary high energy consumption in both DH.

These negative impacts produce a generalized dissatisfaction on the neighbours in S1 and T2, especially because the monthly payments are still the same as before the rehabilitation. In both case studies, neighbours expect that energy rehabilitation would translate directly into economic savings in heating bills.

In Spain (2019 data), the minimum retirement pension (over 65 years old) is between 642,90€ - 835.8€ (Ministry of Social Inclusion, S. S. and M. 2019), and the minimum unemployment benefit is 502€ without children, and 671.4€ with children (European Commission, 2019). Therefore, considering these minimum incomes, heating costs can suppose a 9-12% in S1 block and 13-18% in T2 block, of the household income. In spite of this, defaults are lower than 1-5% in these DH, due mainly to being a cooperative where all households are owners, and having a fixed and expected payment that is well assumed by the dwellers.

These two negative impacts are related to one main cause: the lack of individual regulation and control of the heating system after the envelope's rehabilitation that is essential. Therefore, in 2012, the Energy Efficiency Directive (European Commission, 2012) set mandatory individual metering and charging (IMC) for heating, cooling and Domestic Hot Water (DHW) in multi-apartment buildings with centralized heating systems, when technically feasible and cost efficient. In that way, users should pay for their individual consumption, since individual metering promotes a decrease in energy consumption.

There are some studies which evidence this importance of regulation for achieving lower consumption and energy savings. A case study in Lublin (Poland), where thermostatic radiator valves (TRV) were installed, found energy savings ranged between 7.1% and 23.3%, after their installation, which were amortized over 2.5 winter seasons

Table 3
Model Summary

	Non-standardized Coefficients		Standardized coefficients	t	(95% CI)	p Value (Sig.)
	B	Std. Error	Beta (**β**)			
(Constant)	22,915					
non-rehabilitated						
Rehabilitated	1,771	,150	,644	11,787	(1,472; 2,070)	**,000****
Intermediate						
First floor	-1,124	,184	-,385	-6,108	(-1,490; -0,758)	**,000****
Last floor	,480	,184	,165	2,610	(0,114; 0,846)	**,011****
More than 10						
Extemp7and10	-,383	,222	-,123	-1,722	(-,825; 0,059)	**,089***
Extemp3and6	-,664	,222	-,214	-2,990	(-1,106; -0,222)	**,004****
Less_2	-1,214	,222	-,390	-5,463	(-1,656; -0,772)	**,000****

Note: * **Significant values p**< 0.1; ** Significant values p < 0.05.

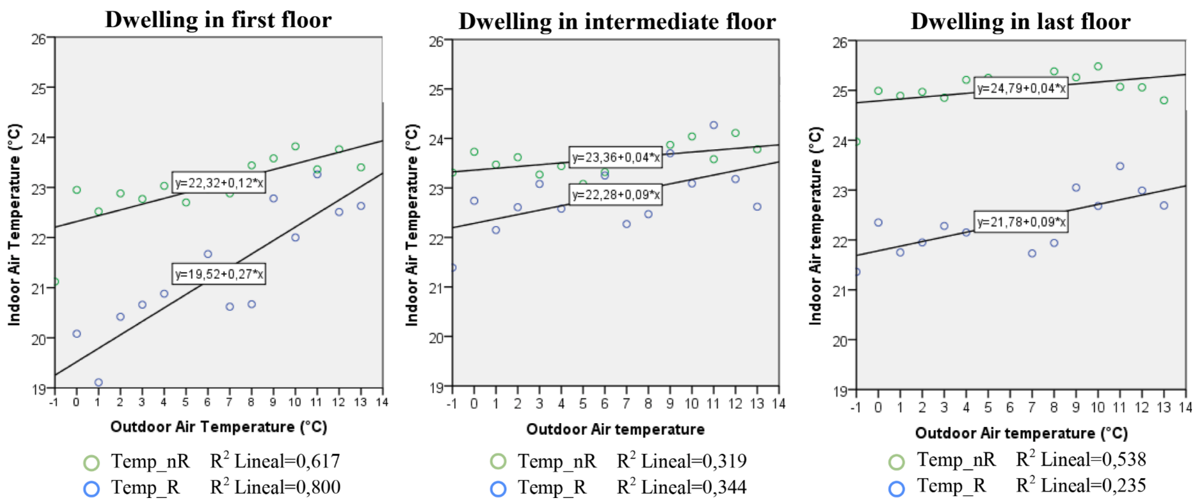


Fig. 5. A: Comparative analysis of indoor temperatures of living rooms in T2 block before (nR) and after (R) rehabilitation

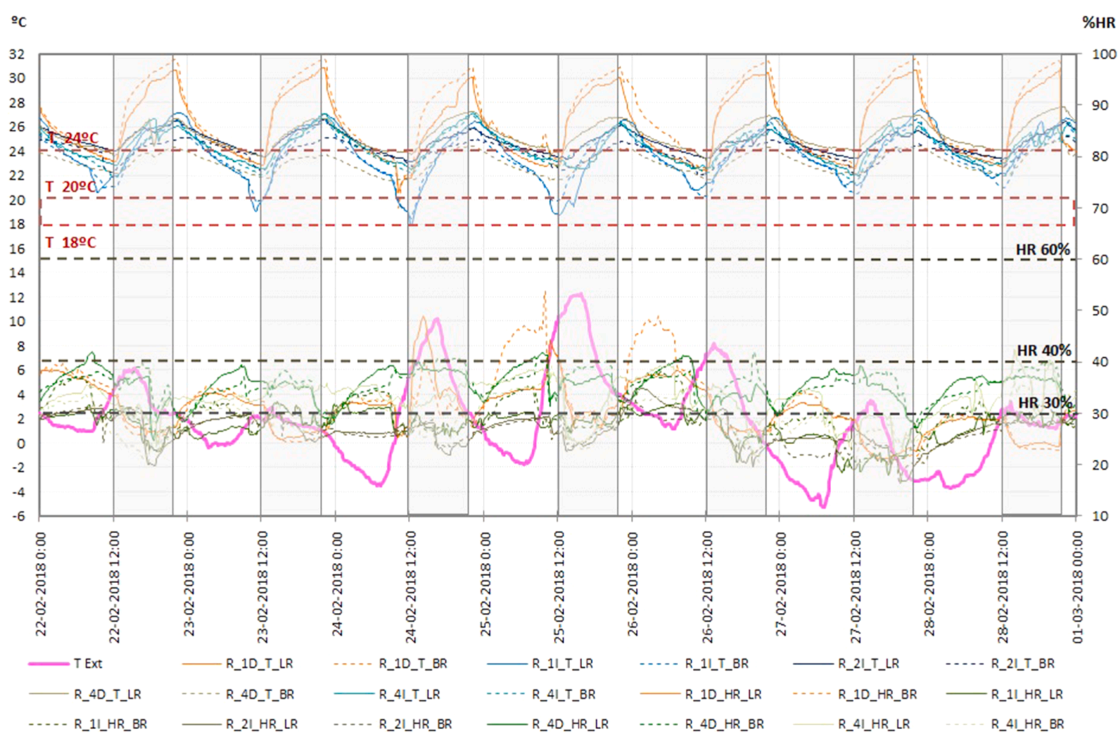


Fig. 6. S1 - rehabilitated (R): Graph of the coldest week of the 2018 winter monitoring campaign, indicating indoor temperature and relative humidity of living rooms (LR) and bedrooms (B).

(Cholewa et al., 2017). Another case study in the north of Spain shows that the implementation of individual metering in centralized systems has reduced standardized energy consumption about 15-20% during the first two years (Terés-Zubiaga et al., 2018).

Despite this evidence, at the time of this study not all phases of the DH rehabilitation process had been completed and individual metering and regulation is not foreseen in the project. Moreover, in these two specific case studies negative impacts are also related with other specific barriers: technical barriers, related to DH network and structure and the social barrier related to the neighbours cooperative system in which both buildings are organised.

In S1 the cooperative has not renovated the system nor-installed IMC per buildings, and therefore cannot distribute the costs according to the individual consumption. This produces a great dissatisfaction among the neighbours of S1, because they are paying the same bill as the neighbours of the group who have not invested in an envelope rehabilitation. Some neighbours even say that "*they prefer to open the windows all day long than to switch off the radiators as the monthly heating bill is the same*". In addition, the dissatisfaction with the impossibility of controlling their own heating system is leading to another critical problem: the disconnection of the DH in favour of individual heating systems. "*Santesteban*" DH originally had 466 dwellings and currently has 366 dwellings, so 15% of the dwellings have been disconnected from the DH.

In block T2 the cooperative does not allow a distribution of the costs according to consumption by block, so the neighbours pay the same as in the rest of the 36 high-rise buildings belonging to the DH. This causes a general dissatisfaction that is increased by the fact that, due to the configuration of the heating system in "*Orvina II*" DH, the dwellings

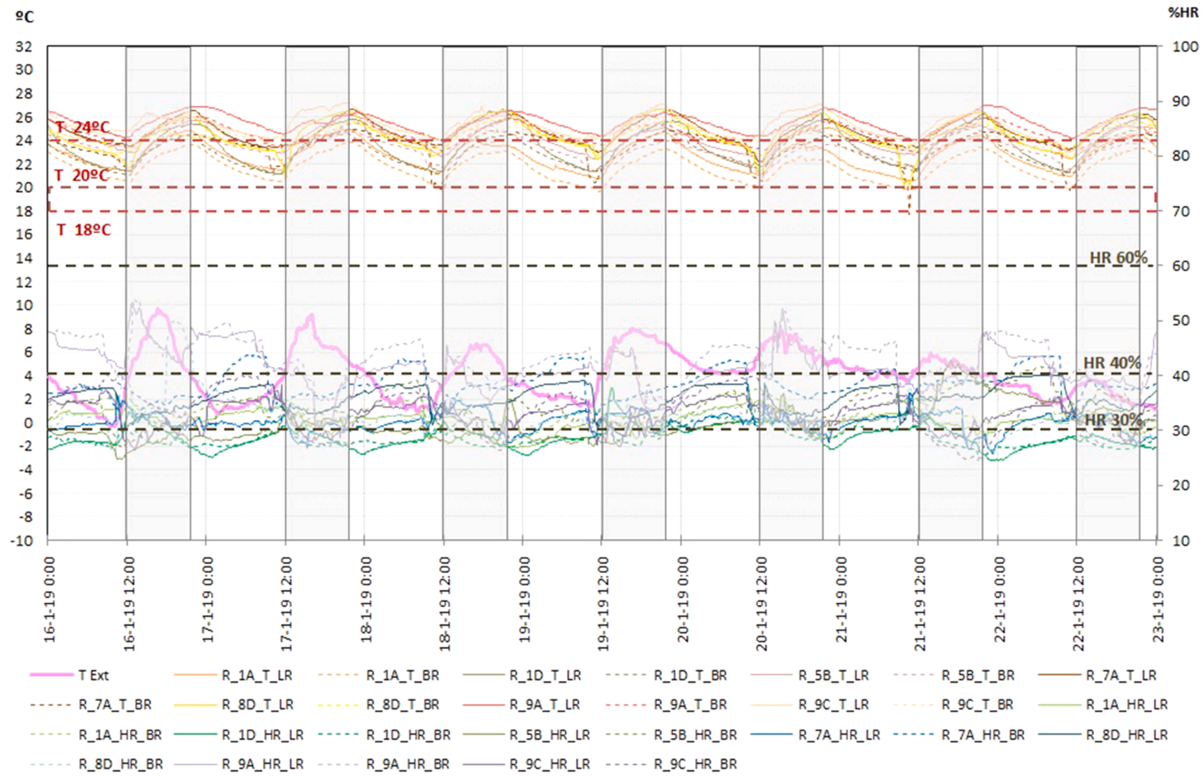


Fig. 7. T2 - rehabilitated (R): Graph of the coldest week of the 2018-2019 winter monitoring campaign, indicating indoor temperature and relative humidity of living rooms (LR) and bedrooms (B).

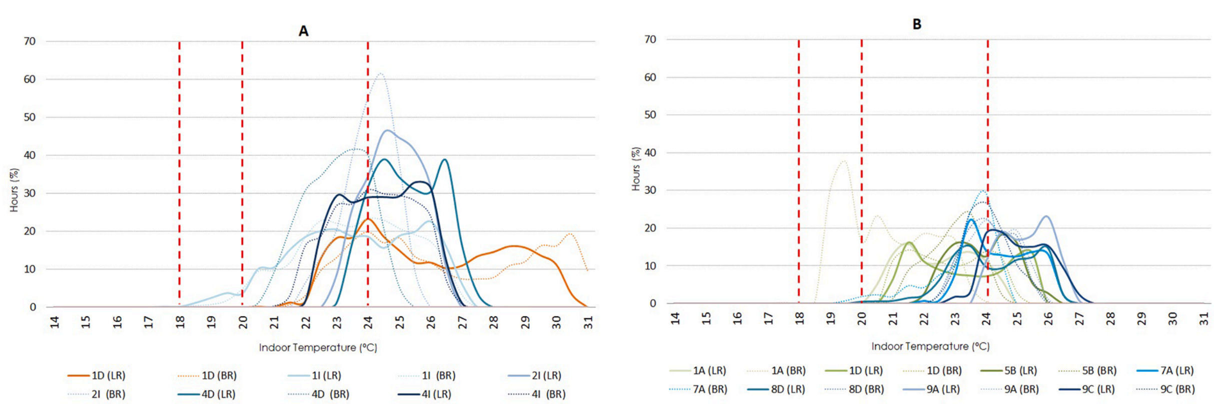


Fig. 8. Frequency of indoor temperatures in S1(R) in the coldest week of the 2018 winter monitoring campaign (A); and Frequency of indoor temperatures in T2(R) in the coldest week of the 2018-2019 winter monitoring campaign (B).

Table 4
S1 energy consumption before and after the refurbishment (nR and R)

	HDD (15°C)	Total District Heating consumption (MWh)	kWh per degree day	Normalized consumption (MWh)	Dwelling consumption* (kWh/m^{2}y)
Oct2011-May2012 (nR)	1405.55	2642	1879.69	2946.97	103
Oct2013-May2014 (nR)	1211.24	2103	1736.24	2722.07	82
Oct2018 - May2019 (R)	1516.3	3271	2157.22	3382.09	127.49

*Note: Since there are no meters per dwelling, consumption has been calculated by dividing total DH consumption by the number of dwellings to which it refers.

Table 5
T2 energy consumption before and after the refurbishment (nR and R)

	HDD (15°C)	Total consumption of both high-rise buildings (MWh)	kWh per degree day	Normalized consumption (MWh)	Dwelling consumption* (kWh/ m^2y)
Oct2017- May2018 (nR)	1420.41	360.32	253.67	397.70	73.65
Oct2018-May2019 (R)	1516.3	327.54	216.01	338.66	66.95
Oct2019-May2020 (R)	1310.7	260.35	198.63	311.41	53.22

*Note: Since there are no meters per dwelling, consumption has been calculated by dividing total consumption of both high-rise buildings by the number of dwellings to which it refers.

cannot be disconnected from the system into individual systems, as in S2. So, they are "*trapped*" in the system, as other studies suggest (Tirado Herrero & Ürge-Vorsatz, 2012).

These consequences show the need to consider some recommendations to improve the DH energy rehabilitation process, to mainly enhance neighbours' satisfaction during this kind of processes. This could ensure that occupants do not move out of the District Heating system into individual systems, which has a negative impact on the overall behaviour of the system, and reduce the survival of this kind of systems (as e.g is real risk in DH of S1). The recommendations are for the neighbours as occupants of dwellings, for cooperatives as managers of the process and for the public administration.

The first and general recommendation is that all agents and actors involved in a DH energy rehabilitation process understand it as complex and long over time. To prevent stakeholders from perceiving a relatively high complexity, which may hinder the processes (Alam et al., 2019; Pellegrini, Bianchini, Guzzini, & Saccani, 2019; Baek and Park, 2012), different steps of the rehabilitation process should be established from the beginning as well as a timetable for these different actions/steps. As an example, Fig. 9 shows the different steps/actions of the rehabilitation process for S1 and T2 with their corresponding impacts depending o–n whether they have been completed or not.

Therefore, the second recommendation is related with the first one, it is specific to the neighbours and it is a key for the success of the project: they should be informed of what to expect at each sta–ge of the process, mainly when related to thermal comfort and changes in payments (Rose et al., 2021). In S1 and T2, only the first step of the energy rehabilitation (improvement of the thermal envelopes) has been completed. At this point, the neighbours should have been informed that, as long as the second step (measuring and regulation) is not fulfilled, temperatures will rise inadequately, consumption will not be reduced and payments will not be adjusted (see section 3). It is also important to emphasize the idea that this is something temporary and is a result of the rehabilitation process.

The third recommendation is specific to cooperatives that should actively implement the most adequate improvements in the system that allow the most cost-effective regulation and metering, and promote a distribution of expenses according to the dwelling ́s heating consumption if some buildings improve their thermal envelopes. This can contribute to foster and accelerate the processes instead of being a barrier. In centralized systems, this cost sharing should be associated with individual control and regulation per dwelling. Thereby the installation of individual regulation and metering has a reflection in users' behaviour because their actions have a direct reflection on the bills. As presented in a case study in Ottawa, if the users are involved in the thermal regulation of their dwellings, they are more aware of the energy consequences of their actions (Burak Gunay et al., 2014). But, in some cases such as S1 and T2, installing individual control and regulation per dwelling is not feasible for some social neighbourhoods because due to the configuration of the interior system, it involves a huge economic and technical investment (i.e. replacing all interior heating systems). Even so, during the time when the heating system is not modified but the envelopes are rehabilitated, cooperatives should make an adjustment of costs and payments between buildings that have invested in their envelopes' rehabilitation and those that have not.

However, once there is individual control per dwelling, it is important to maintain a high proportion of fixed costs in the bill in order to cover the maintenance costs of the whole system and to guarantee minimum temperatures for all users, specially the more vulnerable ones. As an example, in some countries like France, the share of variable and fixed costs is regulated by law in order to protect vulnerable collectives that could "decide" to live in low temperatures (that can affect their wellbeing and health) because they cannot afford the heating costs. Studies show that 10% of excess winter deaths in Europe could conservatively be attributed directly to *fuel poverty* (Hills, 2012).

In Europe, the share of fixed costs varies between 25- 60% (Canale et al., 2019). Dell'Isola et al. found that this variability relies on different characteristics of EU building stocks and on climate conditions (Dell'Isola et al., 2018). In Spain, the Spanish Institute for Energy Diversification and Saving (being the acronym in Spanish IDAE) presents a guide focused on centralised heating and DHW systems which details some recommendations to define fixed and variable costs according to Spanish climate zones, the recommended set-up (IDAE, 2008) being a share of up to 50% of the fixed costs..

Finally, the fourth recommendation is for the administration: they should promote post-occupational studies during the rehabilitation processes (Silva et al., 2017). Monitoring the process would help control the benefits, impacts and barriers of each phase. This kind of studies are fundamental in order to achieve the objectives pursued, that is, to reduce energy consumption and CO_2 emissions and ensure adequate indoor environmental conditions. This recommendation is especially important in case studies where neither dwellings nor blocks have control over their heating system and when there are significant public subsidies to push the regeneration of buildings or neighbourhoods, as in the case studies S1 and T2.

This research was done during the rehabilitation process because the objective was to address its difficulties and barriers; so, it was not possible to analyse the final results after completing the project. Future research can reach the completed process to analyse the achievement of the final goals.

5. Conclusions

Benefits of District Heating on energy efficiency, and the greater potential they have for implementing renewable energies encourage their rehabilitation and up-date. With proper retrofitting, energy-efficient neighbourhoods can be achieved. However, systems as complex and large as District Heating involve long rehabilitation processes in which barriers and challenges can appear and need to be addressed.

In relation to rehabilitation processes, this paper focuses on in-use assessing of the positive impacts and difficulties after the energy rehabilitation of thermal envelopes of two buildings that belong to two different District Heating systems in a social neighbourhood in Pamplona (North of Spain). The analysis of monitoring data before and after the rehabilitation of the thermal envelope reveals that:

Positive impacts found

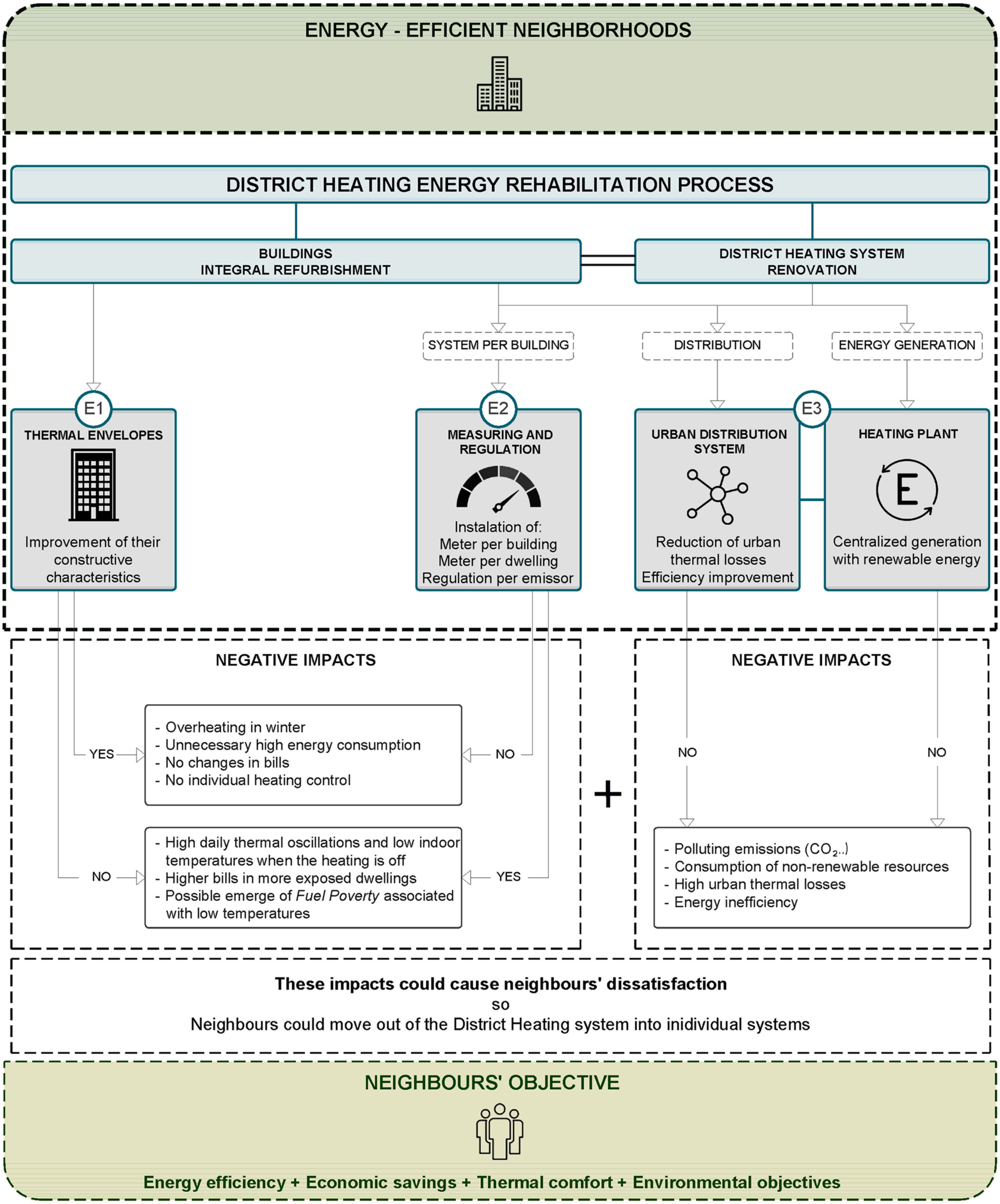


Fig. 9. Energy rehabilitation process of DH. Main impacts and conflicts.

- The improvement of the buildings´ envelopes´ characteristics is significantly associated with an increase of indoor temperatures in winter and higher indoor temperatures in colder periods.

  Difficulties found:

- Due to different technical issues and challenges, the refurbishment of envelopes has not been followed by an adequate regulation and control of the heating system.
- Indoor overheating in winter with maximum average temperatures between 24-26°C. All monitored dwellings are approximately 50% of the time above 24°C and some of them even more than 75%.
- Non-reduction of energy consumption and monthly payments.

Despite the positive impacts, the difficulties produce some dissatisfaction around the neighbours in both case studies. This is leading to critical problems: some of them are disconnecting from DH (in favour of individual heating systems) and others have behaviours contrary to energy efficiency (opening windows to regulate indoor heating temperatures while the heating system is working).

To improve the satisfaction of all the agents and actors involved in these long and complex energy rehabilitation processes and overcome these difficulties, some recommendations are proposed in this paper:

- Neighbours ought to be informed of the benefits and impacts they will have in each step of the process and what they can to expect in each one of them.
- Cooperatives should promote cost-efficient improvements in individual regulation and metering. In case that the system does not allow this, discounts or other benefits should be agreed in buildings that have improved thermal envelope.
- Administrations should accompany this rehabilitation processes, with post-occupational studies to verify benefits and improvements, limitations and barriers of the entire process.

These recommendations will contribute to a better achievement of the final objectives of reducing energy consumption and CO_2 emissions, aiming at the maintenance and improvement of existing District Heating systems, transforming and updating them into low emissions ones.

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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