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Decarbonisation at least cost: an analysis of the optimal portfolio of instruments

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Abstract

Purpose – This paper aims to propose a methodology for assessing an optimal portfolio of investment instruments that minimise the social costs of decarbonising economic activity while improving the environmental objectives proposed in EU legislation.

Design/methodology/approach – The methodology defines the net social cost of decarbonisation related to a portfolio of four instruments: installation of solar PV and wind generation, thermal insulation of households and deployment of heat pumps. The social cost is minimised by restricting it to the minimum level of the targets proposed in the Spanish National Energy and Climate Plan to reduce greenhouse gas emissions, increase generation from renewable sources and reduce energy consumption. The empirical approach also includes differences between regions according to the expected effect for instruments.

Findings – The application of this methodology to the environmental objectives defined in the current Spanish National Energy and Climate Plan for 2030 concludes that it is clearly possible to reduce the social cost of decarbonisation while improving environmental performance through a reorientation of investment instruments. In this case, such a reorientation would be based on a minimisation of efforts in thermal insulation of households and a maximisation of measures aimed at the installation of heat pumps.

Originality/value – The paper proposes a novel methodology for a social cost assessment that improves the allocation of a portfolio of environmental instruments. This portfolio could be extended in further work to include instruments related to transport or support for industrial decarbonisation, such as the deployment of renewable hydrogen, among others.

Keywords Thermal insulation, Heat pump, Decarbonisation, Cost minimisation, Renewable energies

Paper type Research paper

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1. Introduction

All countries are developing a broad set of strategies to advance the energy transition process. These strategies are key to meeting the targets committed to at the Conference of the Parties (COP), in particular the global warming limitation targets of the Paris Agreement. In the case of the European Union, Regulation (EU) 2018 / 1999 on the Governance of the Energy Union and Climate Action has established common rules for the planning, reporting and monitoring main energy and climate objectives. Although some common targets already existed for Member States prior to this Regulation, there was no common framework on the assessment of strategies and measures to be implemented for the achievement of decarbonisation targets.

At the core of this Regulation are the ten-year National Energy and Climate Plans (NECPs). The first NECPs cover this decade and must be consistent with a long-term strategy of net-zero emissions by the middle of this century. The 2030 NECPs are the framework for outlining the strategies to be followed by Member States to contribute to the achievement of the main energy and climate objectives committed to by European Union (EU): reduction of greenhouse gas (GHG) emissions, increase in the share of renewable energies and reduction of energy consumption [1]. The European Commission (EC) assesses those plans, both at EU and Member State level, and publishes reports with recommendations. In the case of Spain, the commitments included in the current NECP were viewed very positively by the EC [2]. In accordance with the Governance Regulation (art. 14), a review of NECPs is underway, with updated objectives expected to be in place in the second half of 2024. This update should reflect the renewed EU-wide targets for GHG emission reductions, renewable generation and energy savings following the European Green Deal and the *Fit for 55* package.

As in other countries, the Spanish NECP includes a long list of measures with the instruments that will be promoted to achieve the environmental objectives pursued. To this end, it defines two scenarios on which it makes a broad set of forecasts for the year 2030. Firstly, a trend (baseline) scenario that would be the result of not adopting the measures proposed in the NECP, so that the values that define it would only be the result of the regulatory measures in force at the initial moment and of the natural technological evolution. Secondly, a target scenario that would be the result of adopting all the measures foreseen in the NECP. To achieve this target scenario, public administrations are expected to contribute subsidies up to a volume of 39.2 billion euros, which in turn will mobilise private investments worth 156.8 billion euros. These would be incremental investments compared to the baseline scenario.

However, the NECP does not prioritise the different instruments proposed in a way that ensures that decarbonisation is achieved at minimum cost to citizens. This issue is of great relevance because the public resources to be committed are substantial. Indeed, the covid-19 prompted the design of a powerful stimulus program through the Next Generation EU (Crnčec *et al.*, 2023). The European agreement stipulates that a very substantial part of the funds (at least 37%) received by Member States should be allocated to support the ecological transition, which also benefits from increased support from the Multiannual Financial Framework. To guide the use of these European funds, the Government of Spain has developed the Recovery, Transformation and Resilience Plan (RTRP). Therefore, and especially in a context in which there is a desire to use a huge flow of public resources in the form of subsidies, it is especially important to advance in a rigorous analysis that guides on how to achieve the maximum effects with the available funds. To this end, it is necessary to clearly identify both the objective to be achieved and the restrictions that condition the fulfilment of this objective.

There is an extensive literature that assesses countries' achievements in implementing European climate change and energy targets over different time periods. For this purpose, different methodologies are applied, such as Data Envelopment Analysis (Guzowska and Kryk, 2021), the multi-criteria decision-making technique (Siksnelyte-Butkiene *et al.*, 2022) and synthetic evaluation indices (Kasztelan, 2021), among others. Alongside approaches that analyse the achievement of objectives, other work has focused on the impacts of the implementation of strategic goals on different variables, such as prices (Paun and Paun, 2017). Two specific issues that have received much attention in relation to the 2030 targets concern European energy efficiency policies (Economidou *et al.*, 2022) and the expansion of renewable energies (Finke *et al.*, 2023; Di Foggia and Beccarello, 2024). Finally, some papers have also analysed the feasibility of mitigation strategies taking into account transition costs. For example, Sofia *et al.* (2020) use cost-benefit analysis to quantify the related social costs and benefits in different sectors (energy, transport and households) for a decarbonisation scenario in Italy in 2030. Their results show positive benefits for all sectors analysed. However, the aim of that paper, like others, is to compare the costs and benefits of decarbonisation in different sectors, but not to assess the relative costs of using one or the other instrument to achieve the targets.

In this context, this work proposes and evaluates a methodology that seeks to ensure economic efficiency in the decarbonisation process. This methodology is applied to a set of key instruments in the decarbonisation process, both on the supply and demand side of energy, allowing to derive the optimal portfolio to address this process. The structure of the paper is as follows. The second section introduces the initial discussion on the portfolio of instruments to be optimised. The third section analyses the contributions of the portfolio instruments to the optimisation programme, determines the objective function with environmental constraints and introduces the geographical dimension based on climate zones. The fourth section shows and discusses the results. Finally, the fifth section concludes with some final reflections.

2. The optimisation of the instrument portfolio: an initial discussion

The Spanish NECP includes a very broad set of instruments and measures to be implemented in order to achieve the envisaged goals. However, there is no detailed breakdown of the effect of each of them on the objectives. In many cases, these are reforms of policy instruments whose individual impact is difficult to assess. For example, improvements in the regulation of access and connection to electricity transmission and distribution networks facilitate and clarify the conditions for the entry of new renewable plants, as well as eliminate uncertainties and conflicts with the system operator, but the concrete impact of this reform is very difficult to discern. In other cases, however, the proposed instruments imply changes in the ways energy is generated or consumed and are measurable. These are, for example, new electricity generation capacities, the transformation of the car fleet or measures to reduce energy consumption (i.e. to increase energy savings).

Instruments for decarbonisation can be complementary or substitutes. For instance, electrification of the car fleet makes more sense the more decarbonised electricity is. Supporting the electrification of the car fleet and the introduction of renewables are therefore two complementary instruments that operate in two key dimensions to reach net zero emissions: the decarbonisation of electricity generation and transport. If public resources are to be allocated to support both, it might be worth considering which instrument to prioritise in a first phase. Nevertheless, as noted above, these two instruments are not alternatives and progress needs to be made on both. Moreover, in this case, the complementarity that arises between the two instruments can be extended to the extent that car batteries are used as a grid stabilisation mechanism (*Vehicle-to-Grid*) that facilitates the penetration of non dispatchable renewable energies. In the case of the electric vehicle, there is a private cost derived from the acquisition of the new vehicle, to which the operating and maintenance costs are added. In addition, there is a reduction of GHG emissions by shifting from (direct) emissions through fuels to (indirect) emissions through electricity consumption.

Sometimes, the instrument to be applied has no alternative. For example, reducing emissions from street lighting can only be done by changing the light source to more energy-efficient LED bulbs, perhaps accompanied by some smart mechanism to optimise the switching on and off procedure. In this case, compared to electric vehicles, there is no change in the energy source, which remains electric and must be more decarbonised. Therefore, there is no impact due to the displacement of one energy source by another and the “private” comparison is established by considering investment costs (replacement of light bulbs) and running costs (lower energy consumption). For a given electricity generation mix, the effect on emissions is derived from energy savings [3].

At other times, however, the instruments are substitutes. A clear example is domestic heating, with two options. On the one hand, one can invest in the thermal insulation of the house. This does not change the energy source, usually gas, but it does reduce the energy consumption required. On the other hand, the source of energy supply can be changed from gas to electricity by using heat pumps. However, both options involve transformation costs, either by investing in insulation (facades, windows, etc.) or by investing in new equipment (heat pumps), so the cost-effectiveness of each option is very sensitive to whether or not the other option is chosen. Therefore, in a context of limited resources, the optimal decision must be the one that has the maximum effect on the desired objective at the lowest possible cost and, in this context, the two options are mutually exclusive.

On what variable can this effect be measured? Strictly speaking, there should only be one ultimate objective to be met, which is the reduction of GHG emissions, as these are the cause of climate change. However, although increasing the penetration of renewables and energy savings are indeed instruments conducive to achieving the goal of decarbonisation, European regulation stipulates minimum targets to be met in all of them. Therefore, taking into account the satisfaction of these objectives, it seems obvious that investment decisions should be oriented towards those instruments that minimise the associated costs. In other words, it does not make sense that the composition of the portfolio of instruments used is the same in Sweden as in Spain, nor can it be the same in a cold region as in a warm region of Spain, since the cost of decarbonising using one instrument or another is very different between geographical areas.

As mentioned above, the objective of this paper is to propose and implement a methodology to identify the optimal portfolio of instruments to address the decarbonisation process. Given the diversity of instruments, four of them have been chosen: investment in solar photovoltaic (PV) generation, investment in wind generation, investment in thermal insulation of houses and investment in heat pumps. These are key instruments in the decarbonisation of energy consumption. In fact, they are crucial for decarbonising domestic energy consumption, given that space heating accounts for 64.4% of energy consumption in EU households, according to Eurostat. They are also important for businesses, although in a much smaller proportion, as heating consumption for thermal comfort is a smaller part of business energy consumption.

The selection of these four instruments does not exclude that others also play a relevant role in the decarbonisation process. In fact, the increase in renewable electricity generation goes hand in hand not only with the electrification of the car fleet and light freight transport [4], but also with the deployment of renewable hydrogen, for which significant volumes of investment are expected in the coming years (IRENA and WTO, 2023). Hydrogen and its derivatives will undoubtedly play an important role in the decarbonisation process of industry and some modes of transport, particularly maritime transport. At the same time, the deployment of renewable generation also requires significant investment in transmission and distribution networks, given the inherently more dispersed configuration of renewable generation relative to the fossil (or, in some cases, nuclear) generation it replaces. The analysis in this paper does not include these other areas of investments for decarbonisation, although the methodology presented can be extended to include them in future research [5].

The initial level of the portfolio of instruments to be analysed has been obtained as the difference between the levels associated with the Spanish NECP target scenario for 2030 and the levels existing in 2020 according to the NECP. Table 1 summarises the amounts of each of the four instruments that will be considered in the initial portfolio. Several considerations are in order. Firstly, remember that this portfolio corresponds to the current Spanish NECP though, of course, the methodology is applicable to any other initial portfolio. Secondly, the current NECP does not predetermine whether the solar panels will be installed in centralised or distributed plants. In this paper, centralised plants have been chosen because they have a lower cost per unit of energy produced than distributed plants. Thirdly, the current NECP does not prejudge whether the wind power plants will be onshore or offshore. This paper has opted for onshore wind farms because, with the current and foreseeable state of technology in this decade, they have a lower unit cost per energy generated than offshore wind farms. Especially given that that the conditions of the Spanish continental shelf make it necessary to opt for floating wind farms, which are practically in pre-commercial development. Fourthly, in the case of investments in thermal insulation of homes, the NECP proposes allocating public aid to thermally insulate 1,200,000 homes between 2020 and 2030. Finally, the Spanish NECP does not refer to the number of households that will install heat pumps, but to the generation of renewable energy produced by this instrument. In particular, it indicates that in the 2030 target scenario, heat pumps will supply 3,523 ktoe/year of renewable energy, compared to 629 ktoe/year in 2020. Using the difference between these two figures and assuming that large part of this difference corresponds to heat generation in the residential sector, the generation produced is equivalent to approximately equipping 200,000 medium-sized homes (90 m^2), with four heat splits per home.

Each of the four instruments described above contributes with different intensity to each of the three proposed objectives (GHG emissions, renewable generation and energy savings) and with different costs. However, the NECP does not guarantee that the proposed mix will achieve decarbonisation at minimum cost. In particular, the objectives of renovating houses with thermal insulation and installing heat pumps are objectives that, while both should pursue the common goal of reducing emissions, act on different mechanisms. In the first case, on the reduction of gas consumption by households and, in the second, on the

Table 1.
Initial portfolio of instruments

Solar PV power (x_1)	Wind power (x_2)	Thermal insulation (x_3)	Heat pumps (x_4)
30,000 MW	20,000 MW	1,200,000 households	200,000 households

Notes: The initial portfolio of instruments refers to the difference between the current Spanish NECP target scenario for 2030 and the levels existing in 2020. For example, the target scenario indicates that 50,000 MW of wind power will be installed by 2030, compared to almost 30,000 MW in 2020
Source: Authors' calculations based on the Spanish NECP

substitution of gas consumption by electricity (with a high share of renewable energy in the generation mix) and by renewable energy captured directly from outside the house.

Therefore, the first step to ensure efficiency in the decarbonisation process is to analyse whether it is possible to optimise the portfolio. That is, if there are different combinations of the same instruments included in the NECP that achieve at least the same environmental objectives associated with the initial portfolio, measured in terms of emission reductions, renewable generation and energy savings, but at a lower social cost.

3. The social cost and contribution of the instruments

3.1 Objective function

The optimal portfolio of instruments is the one that minimises the social cost of decarbonisation, i.e. the one that minimises the cost incurred by society to achieve the targets set. The (net) social cost has four components.

Firstly, the annual payments of the investments associated with each of the four instruments plus, where appropriate, the corresponding annual operation and maintenance (O&M) costs. For the calculation of the annuities, a financial cost of 6% has been used for all instruments, thus avoiding possible biases arising from the recognition of different discount rates [6].

Secondly, the value of the annual savings in natural gas consumption and CO_2 emissions associated with the use of natural gas boilers. That lower consumption, which reduces the (net) social cost, is the result of investments in thermal insulation or heat pumps. Note that the analysis here assesses the social cost of emissions, so it is irrelevant whether or not the household is currently paying for these emissions [7].

Thirdly, the social cost also includes the incremental value of natural gas consumed by combined cycle power plants, as well as the cost of CO_2 emissions associated [8]. These plants have already made the necessary investments for entry in the past and there is idle capacity. Therefore, the entry of combined cycle plants is not considered necessary. Given the low utilisation of combined cycle plants, the costs associated with capacity mechanisms could also be considered. These are mechanisms that reward the availability of some thermal plants or other technologies to provide power at all times to the system operator. However, the regulatory development of these mechanisms in Spain is currently under development [9] and it is not possible to anticipate their cost. This cost will depend on different future regulatory decisions on the quantities (power capacity) to be auctioned, the design of the auction parameters, the reserve price or the technologies that will be able to participate, among others. In any case, these are temporary support measures in addition to the profits that the power plants earn from the sale of electricity and do not affect the functioning of the market and thus electricity prices [10].

In order to properly calculate the social cost, it is necessary to take into account both the direct costs associated with the four instruments and the effects they have on the electricity market balance. This is because, in general, decisions on one instrument affect the equilibrium levels of other instruments. For example, more heat pumps imply more electricity demand, which affects electricity generation market prices and thus renewable energy entry decisions, gas consumption and CO_2 emissions. The characterisation of the equilibrium in the electricity generation market (prices and quantities) is carried out for the 8,760 h of the year 2030, taking as a reference the NECP target scenario and the portfolio of instruments $\{x_i\}_{i=1}^{4}$. Given the high degree of coupling between the Spanish and Portuguese electricity markets, the reference market in the calculations is the whole MIBEL and not only the Spanish market [11]. For Portugal, the reference electricity scenario in 2030 has been constructed based on the National Trends included in the transmission grid development scenarios of the European Association of Transmission System Operators and Transmission Companies (ENTSO-E, 2020). The simulation of the balance of the electricity market makes it possible to obtain the consumption of natural gas in the combined cycle power plants for each hour. Based on this consumption, the value of natural gas consumed and the value of CO_2 emitted are calculated. As noted, both values are part of the (net) social cost associated with this portfolio of instruments.

It is important to underline that, in the calculation of the social cost, only the incremental or avoided cost attributable to the net energy saved is taken into account, without considering taxes/subsidies and "charges" as these affect the private cost observed by investors, but not the social cost. The social cost therefore differs from the private cost faced by investors due to the existence of taxes (or subsidies) or cost overruns included in prices that do not reflect marginal costs.

Of course, the choice of the reference year (2030) conditions the results of the exercise, as the price of electricity and the technological mix on the electricity market will evolve over the lifetime of the different instruments. These two parameters are key. On the one hand, the economic valuation of the energy saved is carried out using its market price. This price is not predetermined, but is calculated as the market equilibrium price in each hour resulting from the supply and demand conditions assumed in the NECP for 2030, as well as the volume of the four instruments evaluated. On the other hand, the effect on emissions cost reduction will depend on which generation source is displaced and what the electricity generation mix is at that time.

Analytically, the social cost (SC) of the portfolio defined by $\{x_i\}_{i=1}^{4}$ is then defined as:

$$\mathrm{SC}\left(\{x_i\}_{i=1}^{4}\right) = \sum_{i=1}^{4} \alpha_i \cdot x_i + F(\Omega; x_1; x_2; x_4)$$

where the social cost is the sum of the direct effects $\left(\sum_{i=1}^{4} \alpha_i \cdot x_i\right)$ which are associated with the portfolio of instruments and the indirect effects that are channelled through the electricity sector, captured by the function F. Specifically, the amounts of these four instruments in the initial portfolio constructed from the NECP target scenario (Ω) are denoted as $x^0{}_1$, $x^0{}_2$, $x^0{}_3$ and $x^0{}_4$ and shown in Table 1. The $\alpha's$ capture the direct impacts of each of the four instruments on the social cost. That is, α_1 (α_2) is the annual payment of the investment in 1 MW of solar PV (wind) capacity plus the annual O&M costs, and it is measured in €/MW per year. By definition, this parameter is positive. α_3 is the annual investment payment required to insulate an average 90 m^2 house, minus the value of the natural gas and CO_2 saved annually in the gas boiler after thermal insulation [12]. The sign of α_3 is not predetermined and it is measured in €/household per year. α_4 is the annual payment required to install a heat pump in an average house of 90 m^2, minus the value of the natural gas and CO_2 saved annually in the gas boiler after the installation of the pump. As before, the sign of α_4 is not predetermined and it is also measured in €/household and year.

Additionally, the indirect effect of the portfolio of instruments, F (Ω; x_1; x_2; x_4), is the value (in €/year) of natural gas consumed and CO_2 emitted in the electricity sector over the 8,760 h of the reference year (2030). It is simulated with all the characteristics of the target *scenario* (Ω) defined in the NECP, but with a portfolio of instruments defined by x_1, x_2 and x_4. Note that x_3 (thermally insulated houses) does not affect the value of F, as thermal insulation only influences household gas consumption, but not electricity demand. However, x_4 (heat pumps) does affect F, as it increases electricity demand. To model the use of the heat pump throughout the year, first the daily heating requirement is calculated, which varies according to the difference between the recorded average daily temperature and a comfort temperature. The hourly electricity consumption of the heat pump is then calculated based on the intra-day heat pump's heating use profile. See Appendix 1 for a more detailed explanation.

3.2 The contribution of decarbonisation instruments and the environmental constraints

In order to obtain an optimal portfolio of instruments, an optimisation problem is considered in which the objective function to be minimised is the social cost associated with the portfolio. This minimisation is subject to three constraints, one for each of the environmental objectives described above: reduction of CO_2 emissions, increase in renewable generation and energy savings (lower consumption). To have a homogeneous metric, the measurements of the social cost and the three environmental objectives are annual and referenced to 2030, as this is the last year of the NECP for which targets are designed.

The contribution of each instrument depends on its idiosyncratic characteristics. It might initially appear that those linked to households (insulation and heat pump) only have effects on savings and emissions, while those linked to generation (PV and wind) only have effects on renewable generation and emissions. However, in almost all cases the instruments contribute to all three objectives. In fact, as will be detailed below, the only exception is thermal insulation, which has no effect on renewable energy production. These contributions are described below.

The installation of solar PV alters the electricity mix during the solar hours. In particular, given that NECP assumes that all coal-fired power plants are closed by 2030, there are GHG emission reductions if power produced by combined cycle gas plants is substituted. In the same sense, the net increase in renewable energy is calculated from the gross energy generated by the installed solar panels, from which the renewable energy displaced throughout the year is subtracted based on the hours in which the injection into the grid takes place and in which renewables form part of the generation mix. It also generates primary energy savings, again considering the energy that was previously produced in the electricity sector with natural gas and is now replaced by solar energy [13]. In addition, the calculation of the contributions on emissions, on (net) renewable energy and on primary energy savings associated with solar PV installation takes into account the interaction with other instruments through electricity market modelling. Finally, the social cost includes the annuity of the investment plus the annual O&M cost, minus the value of the fuel (natural gas displaced) and CO_2 avoided. All of the above applies in the same way to installed wind power, with the only particularity that the substituted energy takes into account the generation mix corresponding to the hours of grid injection of the wind generation.

Insulating homes saves a certain amount of energy consumed in the form of heat per year, for which the Spanish Institute for Diversification and Saving of Energy (IDAE, 2012) provides an estimate that will be used in our analysis. It is assumed that the thermal insulation investment is of the ETICS (External Thermal Insulation Composite Systems) type and that it takes place in a household with an average size of 90 m^2 with a domestic natural gas boiler for heating. It consists of the installation of insulating panels on the facades of the building and on the roof (usually made of rubber fibre, polyurethane or polystyrene) and the installation of aluminium window frames to prevent loss of energy from the home to the outside. Based also on an estimation of the efficiency of the domestic boiler and the emission rate derived from the combustion of natural gas in the boiler, the annual gas and CO_2 emissions saved per household are calculated. However, unlike the other instruments, this intervention does not contribute anything to renewable energy production as the energy input, after insulation, remains natural gas. Finally, the social cost includes the annuity of the investment in the thermal insulation of the house, minus the value of the natural gas saved and the CO_2 avoided.

Additionally, it is assumed that a heat pump is installed in a household that was previously heated with a natural gas boiler. The investment in a 3.5 kWt heat pump with four splits makes it possible to cover the thermal energy needs of a 90 m^2 household from aerothermal energy captured outside the house and from electrical energy. If the SCOP of the equipment exceeds a certain threshold, the energy captured outside is considered renewable energy [14]. The operation of a heat pump that may be representative of those to be installed by 2030 provides 4.5 kWh of heat with 1 kWh of electricity [15]. The annual primary energy savings are obtained by subtracting from the natural gas avoided in the domestic boiler the respective amounts of natural gas and renewable energies used to produce the electricity that powers the heat pump. These quantities are again obtained by considering the generation mix at the times of the year when electricity demand increases because of the use of the heat pump and the electricity to primary energy conversion efficiencies. The avoided CO_2 emissions includes the savings in the gas boiler and subtract the incremental emissions in a gas combined cycle power plant needed to produce the electricity consumed by the heat pump. The renewable energy produced is obtained by adding the energy captured outside the home, plus the renewable energy used to produce the electricity consumed by the heat pump. Finally, for the social cost, the same elements are considered as for insulation: the annuity of the investment and the value of the electricity consumed in the year, minus the value of the natural gas saved by the household and the CO_2 avoided.

The following describes how the three environmental constraints are incorporated into the social cost minimisation problem. Each of these constraints depends, in turn, on the interaction of the instruments outlined above.

The CO_2 emissions (*EMISS*) attributable to the portfolio defined by $\{x_i\}_{i=1}^{4}$ are calculated as:

$$EMISS\left(\{x_i\}_{i=1}^{4}\right) = G(\Omega; x_1;\ x_2;\ x_4) + \beta_3 \cdot x_3 + \beta_4 \cdot x_4$$

where $G(\Omega; x_1; x_2; x_4)$ is the amount of CO_2 emitted in the power sector in the reference year, simulated with the characteristics of the target *scenario* (Ω) of the NECP [16], but with a portfolio of instruments defined by x_1, x_2 and x_4. Note that x_3 (thermally insulated houses) does not affect the value of G because the electricity consumption of the household is not affected by a thermal insulation intervention given the assumption that the household is heated with a natural gas boiler [17].β_3 *and* β_4 (where $\beta_3 \leq 0$*and* $\beta_4 \leq 0$) are the annual reductions in CO_2 emissions due to savings in gas consumption in a boiler, associated respectively with thermal insulation or the installation of a heat pump. *EMISS* is measured in million tonnes CO_2/household and year.

The renewable production (*RENEW*) attributable to the portfolio defined by $\{x_i\}_{i=1}^{4}$ is calculated as:

$$RENEW\left(\{x_i\}_{i=1}^{4}\right) = H(\Omega; x_1; x_2; x_4) + \delta_4 \cdot x_4$$

where $H(\Omega; x_1; x_2; x_4)$ is the amount of renewable energy produced in the electricity sector in the reference year. δ_4 (where $\delta_4 \geq 0$) is the heat captured annually outside the building after the installation of a heat pump. *RENEW* is measured in million toe/household and year.

The primary energy consumed (*PRIMER*) attributable to the portfolio is calculated as:

$$PRIMER\left(\{x_i\}_{i=1}^{4}\right) = I(\Omega; x_1; x_2; x_4) + \pi_3 \cdot x_3 + \pi_4 \cdot x_4$$

where $I(\Omega; x_1; x_2; x_4)$ is the amount of primary energy consumed in the electricity sector in the reference year. π_3 and π_4 (where $\pi_3 \leq 0$ *and* $\pi_4 \leq 0$ are, respectively, the primary energy savings from the reduction of natural gas consumption in a domestic boiler, associated with thermal insulation or the installation of a heat. *PRIMER* is measured in million toe/household and year.

Finally, PLEXOS has been used as a modelling tool for the calculation of the F (and then G, H and I) values. See Appendix 2 for additional details. The technical parameters of the four decarbonisation instruments, both in terms of costs and environmental effects, are detailed in Appendix 3.

3.3 The geographical dimension and the calculation with initial portfolio values

It is natural to expect that the effects of some of the instruments may depend on geographical characteristics. This would affect the value of the unit contributions of each instrument, both on the social cost of decarbonising and on the environmental objectives pursued. The annual electricity generation of solar PV depends on the insolation levels in the geographical area where the plant is installed. Energy savings of thermal insulation and heat pumps depend on the annual heating consumption, which also varies between climate zones. Finally, the efficiency of the heat pump is also different for each climate zone, as it depends on the outside temperature of the house. All these geographical impacts are taken into account [18].

The NECP does not make a geographical distribution of the instruments included in the target scenario. In order to do so, the geographical dimension is introduced by considering five climate zones with differentiated levels of insolation and heating consumption [19]. Table 2 summarises the levels of insolation and heating consumption per household in each climate zone, which are identified by a specific city with illustrative purposes only. The sunshine levels (daylight hours) are based on Royal Decree 661 / 2007, while the heating consumption by climate zone is taken from IDAE (2012).

By including the geographical dimension, the contribution of the three instruments to the social cost function and to the environmental objectives becomes specific to each climate zone. Therefore, the optimisation exercise effectively considers 16 instruments, as wind energy is not geographically distributed. Appendix 4 summarises the specific unit contributions (i.e. not acting through the electricity sector) of each instrument to the environmental objectives and cost function, in each of the climate zones. Two aspects deserve to be highlighted. First, the contribution of the heat pump to the social cost in zones C, D and E is negative, indicating that the value of natural gas and CO_2 saved annually in the gas boiler in all three zones is higher than the respective annual investment. Second, the contribution of solar PV to the social cost does not depend on the climate zone. This is

Climatic zone	Daylight (hours/year)	Heating consumption (kWh_{heat}/year)	Heat pump efficiency
Zone A (Cádiz)	1,883	4,204	4.5
Zone B (Valencia)	1,883	6,412	4.5
Zone C (Barcelona)	1,529	8,896	4.5
Zone D (Madrid)	1,883	12,162	4.5
Zone E (Burgos)	1,529	19,660	3.7
Weighted average	1,725	8,820	4.48

Source: Authors' calculations based on Royal Decree 661 / 2007 and IDEA (2012)

Table 2. Sunshine levels, heating consumption per household and heat pump efficiency, by climate zones

because it includes the annuity of the investment plus the annual O&M costs, which are constant throughout the territory.

Once the initial portfolio of instruments has been distributed and the values of the unit contributions of each of them by climate zones are known, it is possible to calculate the corresponding values of the objective function (social cost) and of each of the environmental objectives for this initial portfolio, which is given by the NECP target scenario. Table 3 shows the corresponding levels. As can be seen, renewable generation amounts to 20.65 Mtoe/year, equivalent to 240 TWh/year. A large part of this production would come from renewable generation plants and only a small part of the renewable production from heat pumps. Specifically, given the distribution of heat pumps by climate zones and the unit contributions, the renewable production from heat pumps would be 120,850 toe/year, equivalent to 1.4 TWh/year. Additionally, the primary energy consumption associated with gas consumption in the combined cycle power plants [20], from which the savings in gas consumption in households due to insulation measures and the installation of heat pumps (in the initial portfolio) have been subtracted, amounts to 8.41 Mtoe/year, which (net of savings) generate emissions of 9.37 $MtCO_2$/year. Finally, the social cost of the initial portfolio is €6.48 billion per year.

Once the initial portfolio has been characterised in terms of the social cost incurred and the environmental targets achieved, it is optimised. This is done on the basis of the environmental contributions achieved by the portfolio in the NECP target scenario. The programme calculates the mix of instruments that, while respecting compliance with minimum environmental targets, minimise the social cost; i.e.:

$$Min\,\mathrm{SC}\left(\{x_i\}_{i=1}^{4}\right) = F(\Omega; x_1; x_2; x_4) + \sum_{i=1}^{4} \alpha_i \cdot x_i$$

subject to:

$$G\,(\Omega; x_1; x_2; x_4) + \beta_3 \cdot x_3 + \beta_4 \cdot x_4 \leq 9.37 \text{ million tonnes } \mathrm{CO_2}/\text{year}$$
$$H\,(\Omega; x_1; x_2; x_4) + \delta_3 \cdot x_4 \geq 20.65 \text{ million toe/year}$$
$$I\,(\Omega; x_1; x_2; x_4) + \pi_3 \cdot x_3 + \pi_4 \cdot x_4 \leq 8.41 \text{ million toe/year}$$

In addition, the minimisation of the objective function is subjected to the fulfilment of a feasibility condition for each instrument *i* in each of the climate zones *z*:

$$0 \leq x_{\mathrm{iz}} \leq \; X_{\mathrm{iz}}$$

where X_{iz} represents the maximum capacity of instrument *i* admissible in climate zone *z*. This variable is determined exogenously according to the characteristics of each zone and its purpose is to prevent the optimisation algorithm from leading to unachievable levels in each instrument and zone. In the case of solar and wind installations, it multiplies the initial capacities in each climate zone by a factor of ten, while in the case of insulation and heat pump, the maximum capacities are determined by the housing stock in each zone.

Table 3. Benchmark levels of social cost function and environmental objectives in the initial portfolio of instruments

Social cost	Emissions	Renewable production	Energy consumption
(M€/year)	($MtCO_2$ /year)	(Mtoe/year)	(Mtoe/year)
6,480	9.37	20.65	8.41

Source: Authors' own work

4. Results and discussion

As mentioned above, the optimisation programme calculates the portfolio of instruments that minimise the *social cost* of decarbonising, while respecting the minimum environmental targets defined by each constraint.

The first line of Table 4 shows the levels achieved in the social cost and the three environmental objectives in the NECP target scenario, while the second line shows those achieved after the optimisation process of the portfolio of instruments. As can be seen, after optimisation the *social cost* has been reduced by almost 11%, equivalent to 706 M€/year or 7,060 M€over the decade 2020–2030. Moreover, two of the environmental constraints are met with levels that improve on those observed in the initial portfolio: this is the case for the level of emissions and renewable production. Consequently, the shadow prices of these constraints are zero, i.e. achieving them does not imply a social cost. Specifically, the level of emissions is reduced by more than half a million tonnes of CO_2/year and renewable energy production is increased by 0.69 Mtoe/year. In contrast, the environmental constraint associated with primary energy consumption does saturate and, therefore, its shadow price is not zero. This means that achieving this constraint does have a social cost and that, consequently, reducing this environmental target would contribute to reducing the cost of decarbonisation and increasing social welfare.

Table 5 shows the optimal portfolio of instruments that results in the levels of social cost and environmental performance shown in Table 4, once the climate zones have been aggregated. The result of the optimisation process indicates, relative to the initial portfolio, an increase in heat pumps by more than 414%, while reducing wind power capacity by 1.6%, reducing solar power by 3.3% and eliminating thermal insulation. As can be seen, the changes are small in terms of the renewable generation capacity to be installed, but substantial in terms of the optimal choice between insulation and heat pump instruments.

Additionally, Table 6 shows these results by climate zones. Firstly, the installation of solar PV panels is just slightly less than the amount proposed to be installed in the initial portfolio (29,000 MW *vs* 30,000 MW). There is a decrease in climate zones C (Barcelona) and E (Burgos), while in climate zones A (Cadiz), B (Valencia) and D (Madrid) the optimal capacity is increased compared to the initial portfolio. In the same direction, the optimal

Portfolio	Social cost (M€/year)	Emissions ($MtCO_2$/year)	Renewable production (Mtoe/year)	Energy consumption (Mtoe/year)
Initial portfolio	6,480	9.37	20.65	8.41
Optimum portfolio	5,774	8.85	21.34	8.41
Variation	−10.9%	−5.6%	3.3%	0.0%

Source: Authors' own work

Table 4. Results of the process of optimising environmental objectives and social costs

Portfolio	Solar PV power (MW)	Wind power (MW)	Thermal insulation (households)	Heat pumps (households)
Initial portfolio	30,000	20,000	1,200,000	200,000
Optimum portfolio	29,000	19,678	0	1,027,841
Variation	−3.3%	−1.6%	−100%	414%

Source: Authors' own work

Table 5. Results of optimising the portfolio of instruments

Table 6. Disaggregation of the optimal portfolio of instruments, by climate zones

	Solar PV power (MW)		Wind power (MW)	
Climatic zone	Initial	Optimum	Initial	Optimum
A (cádiz)	2,537	2,621		
B (Valencia)	7,294	7,802		
C (barcelona)	10,719	9,169		
D (Madrid)	8,713	8,720		
E (burgos)	737	688		
Total	30,000	29,000	20,000	19,678
	Insulation (thousands of households)		Heat pumps (thousands of households)	
	Initial	Optimum	Initial	Optimum
A (cádiz)	101	0	17	0
B (Valencia)	292	0	49	0
C (barcelona)	429	0	71	0
D (Madrid)	349	0	58	948
E (burgos)	29	0	5	80
Total	1,200	0	200	1,028

Source: Authors' own work

capacity to install in wind power is very similar to the initial capacity (19,678 MW *vs* 20,000 MW. Wind energy has not been modelled by climate zones because, within the same climate zone, there is wide heterogeneity in equivalent annual wind hours. Secondly, the optimisation exercise offers significant changes in the optimal portfolio of the other two instruments. It significantly increases the installation of heat pumps from 200,000 to 1,027,841 households, which is concentrated in climate zones D and E. However, in zones A, B and C no heat pumps are installed. The main conclusion is that the initial portfolio constructed from the NECP target scenario has under-weighted the heat pump as an instrument to achieve environmental objectives at minimum cost. At the same time, the NECP has over-weighted thermal insulation of buildings. The result is an increase in the cost of achieving the 2030 targets in the context of the fight against climate change.

The fact that the energy savings benefits associated with housing retrofit programmes are not observed in this estimate may be surprising and requires further reflection. On the one hand, there is a broad consensus on the crucial role of decarbonisation of heat in meeting energy and climate targets. To this end, different countries are opting for different heating technologies, such as solar thermal (Qerimi *et al.*, 2020), district heating (Pozzi *et al.*, 2021) or heat pumps (IEA, 2022). The debate on the replacement of gas for heating by renewable gases, in particular biomethane, is currently open. As for hydrogen, the energy losses in its conversion and transport make it much more efficient, in terms of renewable energy demand, to supply heat to buildings via heat pumps (Gerhardt *et al.*, 2020; Hanto *et al.*, 2024). Furthermore, Thomas *et al.* (2023) conclude that, contrary to expectations, hydrogen would not be less disruptive for consumers than electrification.

On the other hand, even considering a rebound effect, there is little doubt (if any) that thermal insulation reduces building energy consumption and thus emissions. For example, Coyne and Denny (2021), applying the generalised difference-in-difference methodology, conclude that domestic retrofitting produces real energy savings in Ireland. However, different authors underline that the energy savings predicted by bottom-up engineering-based models tend, at least for the building sector, to be higher than actual (Filippini and Obrist, 2022;

Allcott and Greenstone, 2024). In the analysis of energy savings for energy retrofits in buildings, Considine *et al.* (2024) conclude that return in investments depends on the type of specific retrofit, though the application of substantial grants (50% of costs) results in a viable return on investment for home owners. Nevertheless, the evidence is not so conclusive about whether subsidies deliver the savings expected. In particular, Fowlie *et al.* (2018) draw attention to the huge gap between this conventional wisdom and the reality manifested by the largest residential programme in the USA. Their results indicate, on the one hand, the huge gap between predicted and actual savings (in the order of 2.5 times) and, on the other hand, how the investment costs far exceeded the energy savings achieved [21]. Furthermore, it is important to note that this was not a consequence of a *rebound effect* due to a more intensive use of heating after the insulation improvement measures. In sum, the authors obtain a rate of return close to −10%, even when considering the social benefits (lower emissions) from lower energy consumption. This suggests that the low investment in residential energy retrofitting may not actually be due to the presence of market failures (e.g. information asymmetries, imperfect capital markets, group incentives...) that make individuals unable or unwilling to act according to a rational strategy of investing in efficiency gains [22]. On the contrary, the results obtained by Fowlie *et al.* (2018) point out that this reluctance to act is consistent with the non-existence of such gains.

In any case, we should emphasise that energy efficiency retrofit of existing buildings is a broad concept that can include different kind of interventions. In that context, Liu *et al.* (2018) conduct a cost-benefit analysis for different type of projects in northern regions of China [23]. As usual, they observe that energy savings are much lower than the theoretical calculations, and that some particular type of retrofits are cost effective while others do not. In particular, they observe that envelopes retrofit is not economically beneficial though, if replacing windows using appropriate material, retrofit of external windows represents higher cost effectiveness than that of external walls.

The type of thermal insulation assessed in this paper covers both types of retrofitting (windows and external walls) and, as explained before, it is based on average costs and energy savings published by the Spanish Institute for Diversification and Saving of Energy (IDAE). In any case, it should be noted that the methodology is designed to obtain the optimal portfolio of instruments by minimising the (total) social costs across the set of instruments considered, taking into account the interaction between them and policy constraints. Additional investigation would be required to explore different issues raised by the literature, such as the feasibility of hybrid solutions (Yu *et al.*, 2023) or the impact of regulations. With respect to the last one, for example, Lyden *et al.* (2024) point out the effect of introducing locational pricing on the roll out of heat pumps in the UK as far they lead to higher operating costs in regions with high heat demand [24].

To further elaborate on the result obtained in relation to the increased installation of heat pumps compared to the initial portfolio, a sensitivity analysis with two other heat pumps is carried out. Table 7 shows the comparison with respect the initial model (Model 1). In particular, Model 2 uses the parameters of a heat pump whose seasonal coefficient of performance (SCOP) is higher than initially considered. As can be seen, the results do not differ significantly from those previously achieved. The comparison of the optimal portfolio versus the initial portfolio resulting from the NECP target scenario indicates the relative advantage of the heat pump, which in this case increases its installation compared to the previous year. This results in a further reduction in social cost and emissions, while at the same time further increasing renewable production, without changing, as before, the level of primary energy consumed.

Table 7.
Sensitivity analysis with alternative heat pumps

Results/instruments		Model 1			Model 2			Model 3		
		Initial	Portfolio Optimum	Δ	Initial	Portfolio Optimum	Δ	Initial	Portfolio Optimum	Δ
Social cost	M€/year	6,480	5,774	−706	6,475	5,656	−819	6,618	6,189	−429
Emissions	$MtCO_2$/year	9.4	8.9	−0.5	9.4	8.4	−1.0	9.4	9.4	0.0
E. renewable	Mtoe/year	20.7	21.3	0.5	20.7	21.6	0.9	20.6	20.9	0.3
E. primary	Mtoe/year	8.4	8.4	0.0	8.4	8.4	0.0	8.4	8.3	−0.1
Solar PV power	GW	30	29.0	−1.0	30	28.3	−1.7	30.0	28.4	−1.6
Wind power	GW	20	19.7	−0.3	20	19	−1.0	20	22	2.0
Insulation	M households	1.2	0.0	−1.2	1.2	0.0	−1.2	1.2	0.0	−1.2
Heat pumps	M households	0.2	1.0	0.8	0.2	1.3	1.1	0.2	0.4	0.2

Notes: Model 1 = SAMSUNG air-to-air; Model 2 = DAIKIN air-to-air; Model 3 = DAIKIN air-to-water
Source: Authors' own work

Finally, Model 3 refers to a heat-pump with a different technological solution: air-to-water instead of the more common air-to-air. As can be seen, in overall terms this is a less efficient solution than the previous ones. On the one hand, the reduction of the social cost is less intense, the gain of renewable generation is lower, and the restriction of CO_2 emissions is saturated (i.e. it is not possible to reduce CO_2 emission in relation to the initial portfolio). The only advantage over to air-to-air solutions would be a slight reduction in primary energy consumption compared to the baseline scenario with the initial portfolio.

5. Conclusions

This paper proposes and illustrates a methodology to identify the optimal portfolio of instruments to advance the decarbonisation of economic activity. The objective is to minimise the social cost associated with this portfolio, given the environmental objectives of reducing greenhouse gas emissions, increasing the penetration of renewable energies and reducing energy consumption. The optimisation exercise is carried out on the Spanish NECP target scenario for 2030. In this sense, it should be stressed that this is an exercise that does not consider whether the environmental objectives should be different from those approved, but focuses on how to reduce the overall social costs associated with the instruments analysed by improving (or at least not worsening) the environmental performance. In any case, the analysis also provides conclusions on how to optimise social welfare by modifying the objectives included in the NECP. This work also highlights the need to evaluate investment decisions and, of course, decisions on public subsidies that may be granted to support such investments, especially when alternative instruments exist to achieve the environmental objectives pursued at a lower cost.

Although the main contribution of this paper is methodological, the empirical exercise leads to a conclusion of interest: it is possible to modify the amounts of the portfolio of instruments proposed in the Spanish NECP to reduce the cost of achieving the objectives and thus free up resources to improve social welfare. Specifically, this paper has analysed a portfolio of four instruments. The most relevant result is that, in the choice between moving towards electrification of households by replacing gas heating with heat pumps or opting to continue with gas heating and reduce consumption through thermal insulation measures, the first alternative turns out to be more efficient. The exercise, using mainly NEPC information and official sources, shows that the heat pump clearly displaces the thermal insulation solution. Therefore, from the point of view of meeting environmental targets at minimum cost to consumers, the NECP targets for insulation and heat pumps for the existing housing stock should be reconsidered in order to minimise the former and maximise the latter. The parameters included in the modelling are always subject to technological and cost uncertainties and would certainly deserve further empirical validation. However, the main conclusion reached here remains unchanged for reasonable variations of these parameters. In any case, it should be remembered that the analysis developed in this paper does not refer to residential retrofits, but specifically to thermal insulation of homes as an instrument for decarbonisation. Retrofitting is a very broad concept that often incorporates habitability improvements independently of their energy effect. The rationale for public support for such measures is perfectly valid, but is not addressed in this study insofar as it is not aimed at decarbonisation.

There is also an additional argument for this reorientation that has not been taken into account in the empirical exercise, as this only considers the optimal, but static, situation for the year 2030 (the reference year in the NECP). However, it should not be forgotten that 2030 is only a transition year towards the long-term goal of 2050, in which a net zero greenhouse gas emissions balance should be achieved according to the European Climate Law. To achieve this long-term goal, it is necessary to fully decarbonise household energy consumption, which is only possible by switching to a decarbonised energy sources. It is worth recalling that buildings currently consume about 42% of the EU's energy and are responsible for about one third of the EU's energy-related GHG emissions.

This means, firstly, that thermal insulation of buildings will not avoid the need to install heat pumps. Therefore, to the extent that investments (and subsidies) are made in short-term solutions that do not favour the full decarbonisation of energy consumption in the long term, this will make the energy transition of households more expensive. Secondly, it means that the analysis of the cost-effectiveness of thermal insulation in the long-term, should not only take into account the current heating system of households, but also that in the medium term those households will necessarily have to be electrified to comply with a climate-neutral society in 2050 [25]. Furthermore, the analysis has been carried out with air-to-air heat pumps, as the cost of air-to-water systems (underfloor heating) is prohibitive unless carried out in the context of new buildings or major renovations. In this context, it is entirely appropriate that the recent revision of the EU Energy Performance of Buildings Directive (EPBD) has included a ban on subsidies for fossil heating systems from 2025 and a phase-out of fossil fuel boilers by 2040. In any case, as major renovations are carried out on average every 30 years, it is necessary that technical building codes require the installation of underfloor heating with heat pumps in the case of new buildings or major renovations [26]. The challenge for heat transition is even bigger due to, as Lowes and Woodman (2020) emphasise, transformative heat policy remain unpopular for policy makers.

An additional conclusion of the empirical analysis is that, of the three environmental objectives, only the constraint associated with primary energy consumption is saturated. In the case of the other two targets, the constraints are not only met, but also improved in the least costly solution. In particular, CO_2 emissions reach a lower level, while renewable energy reaches a higher level than in the initial portfolio. It seems clear that a Southern country like Spain has a comparative advantage over Northern European countries in stimulating renewable energies, given the relative abundance of resources, and a comparative disadvantage in reducing primary energy consumption through the thermal insulation of buildings, since in Northern European countries the same expenditure on insulation leads to greater savings in energy consumption. This suggests that national governments should concentrate their efforts on instruments with comparative advantages when setting the objectives of the NECP. Furthermore, empirical analysis reveals that only primary energy savings determine the cost of meeting the targets. It suggests that the level of ambition in terms of primary energy savings could be reduced and compensated by increasing the level of ambition in terms of CO_2 emissions and renewable energy use, and still the cost of meeting all three targets would be reduced. In this respect, it is necessary to emphasise that in the fight against climate change the relevant objective is the reduction of GHG emissions, all other objectives being merely instrumental.

Finally, it is relevant that the analysis carried out here is based on minimising the social cost and, therefore, does not take into account the distortions that taxation exerts on the decisions taken by economic agents. In this sense, an optimal way to promote decarbonisation at minimum cost requires an environmental tax approach that avoids distortions in the relative prices of different energies. If prices correctly incorporate social costs, then actors will develop private investments aligned with social cost minimisation. The recent reform of the EU Emissions Trading System to include fuel combustion for heating (and road transport) is a positive step in the right direction, especially as the contribution to the overall decrease of GHG emissions coming from the power generation sector is depleting (EEA, 2020).

Notes

1. The NECPs also includes other dimensions: energy security, internal energy market and research, innovation and competitiveness. There are not explicit objectives in these dimensions, only a cross-border interconnection target of 15%, measured as import capacity over the installed generation capacity of EU countries.
2. All NECPs and EC assessments are available at https://commission.europa.eu/energy-climate-change-environment/implementation-eu-countries/energy-and-climate-governance-and-reporting/national-energy-and-climate-plans_en.
3. A relevant "rebound effect" would absorb part of the emission reduction effect linked to lower electricity consumption. See Herring (2006) for evidence on this particular case.
4. See Danielis *et al.* (2022) for an analysis of transport decarbonisation in Europe.
5. It should be noted that, unlike investments in power generation or in renewal of thermal, industrial or transport equipment, which are mainly private investments in a liberalised environment, investments in electricity grids are developed in all countries in a highly regulated environment, as they are natural monopolies. An additional question, which is beyond the scope of this paper, concerns whether and how emissions associated with the entire value chain of each instrument should be considered.
6. See Steffen (2020) for a discussion on the estimation of the cost of capital in renewable projects and a review of methodological approaches.
7. The reform of the EU Emissions Trading System (Directive (EU) 2023/959) has extended it to buildings emissions, among others, in a separated system (ETS2) that will be launched in 2027.
8. There is a huge literature on gas and CO_2 price forecasting, as with many other commodities. Several factors influence price volatility, such as economic uncertainty (see e.g. Ashena *et al.*, 2024). Because this paper uses the NECP scenarios, the gas and CO_2 prices set in the NCEP are assumed (i.e. they are exogenous). This is not the case for electricity prices which, as will be seen, are endogenous.
9. The regulation of temporary capacity mechanisms for power generation in the EU requires an extensive process that starts with a prior analysis of domestic resource adequacy, carried out both at European (ENTSO-E) and national level (domestic system operator).
10. The share of capacity payments to be considered would be only those attributable to incremental investments in solar and wind generation capacity.

11. According to the Power Market Operator (OMIE), there was market coupling between Portugal and Spain in 97,1% of the hours in 2022.

12. The exercise uses a high efficiency natural gas boiler (efficiency rate of 98%) which corresponds to a condensing boiler. The emission rate is 0.201 $tCO_2/MWh = 2.34\ tCO_2/toe * 0.086\ toe/MWh$.

13. One unit of electrical energy produced in a gas-fired power plant (combined cycle) requires approximately two units of primary gas energy (2:1 ratio). The methodology of energy balances (see Eurostat, 2019) indicates that in the case of wind and solar energy, where there is no thermal transformation and therefore no heat loss, electricity production is used for the measurement of primary consumption. This implies that, in these cases, the ratio of primary to final energy is 1:1.

14. Directive 2009/28/EC sets out in Annex VII how to calculate the aerothermal renewable energy attributable to the use of a heat pump. For the calculation, and in accordance with the Decision 2013/114/EU, heat pumps are required to have a minimum SCOP of 2.5. The SCOP is a seasonal performance coefficient, the value of which depends on the outdoor temperature conditions and manufacturers are obliged to inform consumers about the performance of the appliance they purchase in each climate zone. See Appendix 1.

15. In the calculations detailed below, a Samsung model has been used as a reference, the technical data of which are given in Appendix 3. In a subsequent sensitivity exercise this model is changed.

16. Note that, although the electricity market equilibrium is unique, the value of F (in the social cost) captures the value of natural gas consumed and CO_2 emitted in the electricity sector over the year, while G captures the relevant dimension for the environmental constraint, which in this case it is the tonnes of CO_2 emissions.

17. As noted above, while insulation and switching to a heat pump are not incompatible decisions, it is assumed that the household will adopt one or the other, but never both simultaneously.

18. It should be noted that this analysis ignores the fact that many households install the heat pump in their homes because of the need to provide cooling during the summer. Consequently, by omitting the welfare derived from this use, the incremental investment cost of the heat pump for heating is overestimated.

19. The climate zones are a simplification of those included in *Appendix B* of the Ministry of Housing and Urban Agenda (2022). The simplification consists of assigning the entire province to the same climate zone that characterises its capital, although in reality several climate zones coexist in the same province. As this paper is based on the peninsular system, the Canary and Balearic Islands, Ceuta and Melilla, are not included.

20. Following the standards used by the System Operator (Red Eléctrica de España), it is assumed that the efficiency of a combined cycle power plant is 2.09 kWh(gas)/kWh(electric), measured at the point of consumption. Although efficiency is usually measured at the exit point of the substation, in this report it makes sense to measure it at the point of consumption. In this case, the efficiency is lower (higher needs of kWh of gas to produce one kWh of electricity) because the losses due to the transport and distribution of this energy must be added. Finally, the emission rate is 0.41 tCO_2eq/MWh.

21. It is worth emphasising the magnitude of the experiment: 7 million households, all of them after undergoing a cost-benefit test based on engineering estimates, receive an average of $5,150 for thermal insulation of walls and ceilings, reduction of infiltration and replacement of appliances.

22. See, for example, López-Bernabé *et al.* (2022).

23. Carratt *et al.* (2020) provide a critical review of studies that have applied experimental and simulation techniques to evaluate thermal retrofits, distinguishing different passive design interventions.

24. See OFGEM (2023) for an analysis on the effects of introducing locational wholesale pricing.
25. In their revision of home energy retrofit, Saffari and Beagon (2022) point out that "*Current policy targets driving decarbonisation have increased the focus on energy supply and decreased the primacy of the fabric-first approach. large-scale home energy retrofit programmes using purely fabric-first approaches have also struggled to meet energy-use targets because of occupant-caused rebound and prebound effects*".
26. In this regard, Sandberg *et al.* (2021) conclude on the remarkable effect that can be expected from future stricter regulations for new energy efficient and zero emission buildings (ZEB).
27. IEA (2022) offers a complete analysis on technical and economic issues related to heat pump deployment.

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Appendix 1. Calculation of the increase in electricity demand associated with the installation of heat pumps.

A heat pump transfers heat from a cold source (outside environment) to a hot source (inside the house) by means of a work input in the form of electrical energy. This counter-natural flow is achieved by the operation of a motor that raises the pressure and heats a refrigerant fluid in the form of gas [27]. The heat transfer can be from different external media (air, water, earth) to different internal media. Accordingly, heat pumps can be air-to-air, ground-to-air, air-to-water, etc. In this paper, an air-to-air heat pump is evaluated, as it is by far the most common solution in existing buildings. However, new buildings often incorporate air-to-water heat pumps (underfloor heating). In addition, in the vast majority of cases, heat pumps are reversible, as the reverse gas operation allows cooling to be provided instead of heating.

It is important to note that a significant part of the thermal energy provided by the heat pump comes from the outside, making the heat pump very energy efficient. This external energy is considered renewable, as it does not use any exhaustible input. The ratio between the total energy yielded by the system (generated + transferred) and the energy used by the compressor, evaluated under certain temperature conditions that vary seasonally, is the SCOP index (Seasonal Coefficient Of Performance) which, due to the above, has values greater than 1. For example, a SCOP = 4 indicates that only one fourth of the energy needed to heat a house comes from the electricity consumed, while the rest comes from the energy extracted from an external source.

The increase in power demand $\left(DP_t^z\right)$ in hour t due to the installation of a heat pump that replaces a gas boiler in an average Spanish household of 90 m^2 in climate zone z, is obtained by dividing the heating demand in that hour and climate zone $\left(DH_t^z\right)$ by the efficiency of the heat pump in the climate zone ($SCOP^Z$):

$$DP_t^z = \frac{DH_t^z}{SCOP^z}$$

where the heating demand is calculated according to the following expression:

$$DH_t^z = DH^z \cdot \frac{\Delta T_t^z}{\sum_{t=1}^{365} \Delta T_t^z} \cdot \eta_h$$

and where:

DH^Z= annual heating demand in zone z (see values in Table 2):

$$\Delta T_t^z = \begin{cases} (17^\circ - Temp_t^z) & if\,(17^\circ - Temp_t^z) \geq 0 \\ 0 & if\,(17^\circ - Temp_t^z) < 0 \end{cases}$$

$Temp_t^z$ = average temperature of the day corresponding to t in zone z. 17° is considered the “*comfort*” temperature, below which the heating is activated in the household.

η_h = time profile of heating demand during the day $\left(\sum_{h=1}^{24} \eta_h = 1\right)$. These values have been obtained from the *INDEL Project, Atlas de la demanda eléctrica española,* elaborated by the System Operator (Red Eléctrica de España*)*.

Appendix 2. Modelling the electricity sector.

The optimisation exercise carried out in this work requires the incorporation of an equilibrium modelling of the electricity sector. Through it, changes in any of the three instruments considered (solar PV, wind and heat pumps) affect all agents (consumers and generators) participating in the market. This is not the case for thermal insulation of a house with thermal heating (e.g. natural gas) as insulation reduces the consumption of natural gas but does not affect electricity consumption and, therefore, does not affect the electricity system.

Thus, for example, the installation of additional wind power capacity means the contribution to the electricity market in each of the hours in which the generation provided by new capacity is injected into the grid. Except in situations of renewable curtailments, this emission-free energy displaces the production of thermal technology (usually natural gas) so that primary energy consumption and emissions are reduced. The installation of heat pumps, in turn, leads to an increase in electricity demand during the hours in which they are used. This can have the opposite effect to the previous one, i.e. favouring increased electricity production, which initially will be done with combined cycles, but which will induce a greater entry of renewable plants.

Consequently, the interaction of these three instruments in the electricity sector modifies the ability of each instrument to contribute to each of the environmental objectives. It requires calculating the contribution of the portfolio of instruments to the cost function (F) and to each environmental constraint (G, H and I) by jointly modelling the electricity market as the optimisation algorithm modifies the portfolio of instruments. Specifically, a model based on PLEXOS has been used to simulate the Spanish and Portuguese electricity systems throughout the 8,760 h of the year. PLEXOS is a commercial software, owned by *Energy Exemplar*, which allows the optimisation of electricity systems and is widely used by companies and electricity system operators.

The model incorporates the conditions of the Spanish NECP *target scenario* in 2030 together with the Portuguese electricity market. These conditions mainly concern demand, generation capacities, fuel costs and cross-border interconnections. The model allows estimating gas consumption, emissions and hourly prices in response to specific variations of each instrument considered in the analysis, obtaining the values of F, G, H and I associated to each instrument portfolio $\{x_i\}_{i=1}^{4}$ in each of the iterations of the optimisation algorithm. Since PLEXOS is an external tool to the cost minimisation model (although the latter uses its results in the optimisation procedure), a limited number of simulations of the electricity market in equilibrium have been carried out, permuting multiple combinations of each of the three portfolio instruments involved in the electricity sector, and interpolating the values resulting from intermediate changes.

Appendix 3

Table A1. Main technical parameters of decarbonisation instruments

	Solar PV	Wind	Insulation	Heat pump (Model 1)	Heat pump (Model 2)
Reference unit	1 MW	1 MW	ETICS in a 92 m^2 home, in a block of flats built in 1975	Samsung WF-12ULTRA 4 kWt SCOP (2°C) of 4.48	Daikin TXA20AW 3.5 kWt SCOP (2°C) of 6.26
Investment cost	500,000 €/MW	1,066,000 €/MW	10,000 €/household	849 €/unit	797 €/unit
Useful life (years)	30	20	50	15	15
O&M cost (€/MW and year)	9,000	21,000	0	0	0

Sources: For photovoltaic and solar installations: NT (National Trends) and DE (Distributed Energy) scenarios of ENTSO-E (2020). For thermal insulation: IDAE (2012). For heat pumps: manufacturers' technical references

Appendix 4

	Zone	Panel Solar PV (1 MW)	Wind farm (1 MW)	Thermal insulation (1 household)	Heat pump (1 household)
Social cost (α_i) (€/unit/year)	A			597	192
	B			576	91
	C			523	−22
	D			435	−172
	E			285	−514
	Total	45,300	98,400		
Emission reductions (β_i) (tCO_2/unit/year)	A			0.58	0.86
	B			0.67	1.32
	C			0.91	1.83
	D			1.31	2.50
	E			1.98	4.04
Renewable production (δ_i) (toe/unit/year)	A				0.28
	B				0.43
	C				0.59
	D				0.81
	E				1.23
Primary energy savings (π_i) (toe/unit/year)	A			0.27	0.40
	B			0.31	0.60
	C			0.42	0.84
	D			0.60	1.14
	E			0.91	1.85

Note: The environmental contributions β and π have been expressed as positive values, so that a higher value reflects a greater reduction in emissions and energy consumption (i.e. greater savings)
Source: Authors' own work

Table A2. Specific unit contributions to the cost function and environmental objectives, by climate zones

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