This article is a preprint. Please cite the published version: 10.1016/j.enpol.2022.113211

Energy-efficiency policies for decarbonising residential heating in Spain: a fuzzy cognitive mapping approach

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Abstract

Decarbonising residential heating poses a major challenge for the energy transition, but the policy attention devoted to and the support provided for it seem limited. There is a rather limited consideration of the perceptions of households, which play a large role in this sector. This in turn may affect the effectiveness of policy instruments. This study contributes to a better understanding of the various perceptions held by key stakeholders, in particular about what can be done to reduce residential heating bills and how. We use a participatory method based on Fuzzy Cognitive Mapping (FCM), which accounts for the behavioural complexity of the transition in residential heating and provides a better understanding of policy instruments in terms of stakeholder perception. We then test combinations of policy instruments based on expert opinion and identify the most effective ones based on their perceptions. Our analysis indicates that environmental education and information are perceived to reduce heating bills by a very significant amount. Taxes are perceived to be more effective than subsidies. We also show that policy packages are considered essential: when policy instruments are combined the effects perceived are cumulative, resulting in a much greater expected impact on heating bills and energy consumption.

Highlights

- Perceptions from different stakeholders play a central role in the heating transition process.
- A Fuzzy Cognitive Mapping approach reveals unexpected effects, providing insights for effective policies.
- The effects of combining policy instruments are greater than when instruments are used in isolation.

Keywords: Energy-efficiency policy instruments; Policy simulation; Residential heating decarbonisation; Fuzzy cognitive mapping.

1. Introduction

Providing heating for homes, industry and other applications accounted for around half of global final energy consumption in 2021 (IEA, 2021), and that consumption accounted for 40% of energy-related greenhouse gas emissions (GHG) (IRENA et al., 2020). Heating in residential buildings accounted for 64% of the European Union's (EU) final energy consumption in 2019 (Eurostat, 2021). Given the EU's commitment to cut its GHG emissions by at least 50% and towards 55% by 2030 (compared to 1990 levels) and to achieve net-zero GHG emissions by 2050 (EC, 2019), the decarbonisation of residential heating plays an important role in fulfilling EU climate and energy goals (Nijs et al., 2021). To address that decarbonisation, the residential sector would have to undergo the greatest reduction in energy demand for heating and cooling, ranging between 19% and 23% by 2030 (compared to 2015) (EC, 2020a). To reach this target, the EU has emphasised the following main areas: energy efficiency (building renovation, efficiency of heating and cooling supply), the phase-out of fossil fuel-based boilers and increasing the share of renewable energy heating systems (Braungardt et al., 2021). These actions require target-oriented policies (Nijs et al., 2021) and other national policies to address challenges and barriers specific to each Member State (Toleikyte and Carlsson, 2021).

Decarbonising heating is a complex challenge with many interdependent factors (e.g. technological, behavioural, economic, socio-cultural, institutional) (Csutora et al., 2021; Knobloch et al., 2019; Narula et al., 2020) and one that involves many stakeholders (consumers, builders, firms, policy-makers) (Gago et al., 2012). To meet this challenge, the preferences of all the stakeholders involved need to be factored into the analysis so that better policies can be designed (Falcone et al., 2021; Lange and Cummins, 2021) and the effectiveness of those policies can be maximised. Common knowledge from stakeholder participation can bring all stakeholders involved to a more conscious behaviour so as to better support and accept policy levels for energy transition (Falcone, 2018; Falcone et al., 2021; Itten et al., 2021). Additionally, the literature on governance suggests that participation by different stakeholders in the decision-making process can be an effective tool for resource management (Lange and Cummins, 2021) because it can harness the power of diverse perspectives, build coalitions and promote cooperation rather than competition (Sovacool and Martiskainen, 2020; Sovacool and Van de Graaf, 2018). In this regard, the heating transition must take place from a governance point of view, involving multiple stakeholders none of whom have decisive power (Smith et al., 2005). The importance of local stakeholders in achieving energy transitions was noted in the 2015 Paris

Agreement (Falcone et al., 2021; Galende-Sánchez and Sorman, 2021; UNFCC, 2015). Indeed, the empowerment and engagement of citizens are seen as strategic to meeting the EU's energy targets in the clean energy transition (EC, 2019; Wahlund and Palm, 2022).

The literature on participatory approaches recognises the need to identify the roles and perspectives of local stakeholders. For example, Mendonça et al. (2009) and Sperling et al. (2011) demonstrate that local stakeholder participation is an effective tool in supporting structural, cultural and practical changes in energy planning in Denmark (Falcone et al., 2021). A case study on the implementation of a renewable energy project in Switzerland shows that the personal values of local stakeholders and their interests must be represented during the decision-making process (Díaz et al., 2017). Lange and Cummins (2021) find that civil society is missing from the negotiation process for a renewable energy project in Ireland, and that added cost could have been avoided if community stakeholders had been more engaged in the planning process from an early stage and if place-based understanding had been considered more strongly. In this sense, (Itten et al., 2021) show that sustainable heating projects need to be supported by clear political commitment, as it may otherwise be difficult for individual members of the community to step up to leadership roles. Local stakeholders are thus key actors in transforming perceptions into tangible experiences on energy transition, fostering social acceptability and motivating technological choices (Falcone et al., 2021; Sisto et al., 2018).

However, the understanding and consideration of stakeholders' perceptions about the decarbonisation of residential heating is still quite limited. Approaches that examine household decision-making processes concerned with residential heating show the importance of behavioural aspects, given the heterogeneity of household characteristics and perceptions (Kastner and Stern, 2015; Levesque et al., 2019; Wolff et al., 2017). These factors, uncertainties and behaviours explain some of the barriers to energy-efficiency improvements. For instance, a look at the main barriers to heating replacement (cognitive limitations, the principal agent problem, financing costs and other investment priorities and lack of capital) reveals that it is unlikely that all households will choose the same cost-optimal solution (Knobloch et al., 2021). These barriers (Gerarden et al., 2017; Gillingham and Palmer, 2014; Jaffe and Stavins, 1994; Linares and Labandeira, 2010; Ramos et al., 2015) and particularities must be taken into account if a proper understanding is to be obtained. In that context, considering that different stakeholders may have different scopes and perceptions may help to address these particularities and the major barriers. To further the low-carbon residential heating transition, a participatory process needs to be established that enables stakeholders to (i) define the main drivers for and barriers to heat decarbonisation; (ii) assess measures which could decarbonise heating consumption; (iii) propose policies; and (iv) assess impacts through scenario simulation.

Contributions in this field have concentrated mainly on including representations of household behaviour and preferences (Knobloch et al., 2021; Sovacool and Martiskainen, 2020). However, to our knowledge there are no broad-based studies that seek to learn how households perceive the different policy instruments that may be used to promote sustainable heating.

This paper sets out to fill that gap by employing a policy fuzzy inference simulation that incorporates the preferences of all stakeholders involved. Such a methodological approach can help to understand the complexity and interactivity of the current heating system and identify the most influential policies with a view to steering the decarbonisation of residential heating.

In this regard, our research shows the importance of broadening the debate on heating transition by incorporating the perceptions of expert stakeholders such as academics and energy experts. Academics and universities can contribute new designs, criteria, approaches and concepts (Fischer and Newig, 2016; Goess et al., 2015; Shahvi et al., 2021). Energy experts are also considered key actors because they bring competitive products and services to the market (Sorman et al., 2020). Based on the literature, the perceptions of energy experts can be used as sensors, to locate synergies and potential bottlenecks around the energy transition, such as institutional and regulatory systems or infrastructures unsuitable for change (Foxon et al., 2010; Smith et al., 2005).

For this purpose, we use the so-called Fuzzy Cognitive Mapping (FCM) method for policy simulation. It is built upon a paper already published (López-Bernabé et al., 2020). By applying the FCM method, we seek to understand the different perceptions of stakeholders about energy efficiency policy instruments and provide some insights for effective policy design. FCM is a participatory, semi-quantitative technique in which a weighted causal network of a situation or system is produced by an interviewee or selected group of agents (Groumpos, 2010; Jetter and Kok, 2014; Kosko, 1986). That is, it enables a map of complex concepts to be drawn up based on the perceptions that the participants may have on certain issues, topics and relationships, thus bringing to light interesting findings with respect to the expected behaviour of participants. López-Bernabé et al. (2020) show that the determinants of heating bills include not just economic variables such as energy price and income but also technological energy-efficiency variables such as investment in insulation or the use of thermostats or other temperature regulating devices. They also find differences between the views of the three groups, and show that the policies mentioned by academics and energy experts differ from those mentioned by households. For example, academics and energy experts consider that taxes could be used to reduce energy consumption through policies such as taxing bad habits in energy consumption or taxes on fossil fuels. Households do not mention taxes at all but focus on the role of subsidies in helping alleviate energy poverty. Another difference is that academics and energy experts seem to support environmental education policies directly while households say very little about them. In the light of this, we set out here to answer the question of what policy instruments might be most effective in bringing about a low-carbon transition in the household heating sector.

Our survey was carried out in Spain, as we deem it an interesting case from which many insights can be extrapolated to other European countries. Demand for heating is lower in Spain than in many other parts of Europe due to a warmer climate. Just 42% of the energy demand from residential buildings in 2019 came from heating (IDAE, 2021), but the country still provides a very interesting case study for the deployment of low-carbon residential heating strategies. The main reasons are that, unlike the EU average, where natural gas is the most widely used fuel for residential heating, Spain uses several different energy sources. In 2019, 40% of the energy used for residential heating came from biomass and around 1% from other renewables (mainly solar thermal and, to a lesser extent, geothermal). Oil and petroleum products accounted for 28%, natural gas for 23%, electricity for 7% and other fossil fuels for 0.9% (IDAE, 2021). As a case study, Spain provides insights for countries with similar heating consumption patterns (e.g. Greece, which uses several different fuels, mainly natural gas (16%), oil and petroleum products (46%) and biomass (31%)). These data show that if biomass is discounted then renewables are one of the smallest supply sources for residential heating in Spain. Thus, Spain can provide insights for countries in eastern and southern Europe with no plan to ban any type of fossil fuel heating systems but with ambitious national measures for the decarbonisation of residential buildings (Nijs et al., 2021).

Our study also provides many useful recommendations for Spanish policy-makers. The national policies and measures towards decarbonisation of buildings presented in the National Energy and Climate Plan (Toleikyte and Carlsson, 2021) indicate that there is no specific plan to phase out fossil fuel heating systems in Spain and there are no forecasts for the share of renewable technologies in heating and cooling. Nonetheless, the country plans to promote ambitious building renovation targets to 2030 with thermal envelope systems and renovation of thermal heating and air conditioning systems. The insights provided by the paper on stakeholders' perceptions will be essential for deploying these actions efficiently and effectively.

The paper is structured as follows. Section 2 reviews literature associated with the policy instrument options available for decarbonising heating. Section 3 describes the research methodology. Section 4 presents and discusses the results. Section 5 concludes.

2. Policy interventions for decarbonising heating

Political attention and support for heating decarbonisation seems limited despite the large proportion of final energy consumption in the EU accounted for by heating. In 2016, the European Commission proposed an EU heating and cooling strategy to explore the main issues and challenges and integrate efficient heating and cooling into EU energy policies (EC, 2016). More recently, the decarbonisation of heating in buildings has been addressed across key EU legislation including (i) the Energy Performance of Buildings Directive (EPBD) (Directive 2018/844/EU); (ii) the Renewable Energy Directive (Directive 2018/2001/EU); the Energy Efficiency Directive (Directive 2012/27/EU); and the Ecodesign Regulation (813/2013/EU) implementing the Ecodesign Directive (2009/125/EC). The EPBD is currently under revision (EC, 2021a) with the aim of introducing provisions to support the objectives of the Renovation Wave Strategy (EC, 2020b). The aim is to increase actions and investments with the target of at least doubling the annual energy renovation rate of buildings by 2030 and to foster deep retrofits. It was (and still is) considered as an opportunity to lead a green economic recovery from the crisis sparked by the coronavirus pandemic, supporting Small and Medium Enterprises (SMEs) and local jobs (BPIE, 2020). The revision of the Renewable Energy and Energy Efficiency Directives (EC, 2021b, 2021c) seeks to set quantitative requirements for minimum levels of energy from renewable sources in buildings and support the phase-out of fossil-fuel boilers in regional and local planning. The EU also highlights the application and further development of ecodesign and energy labelling measures to support the phase-out of fossil fuels for heating in buildings through strengthened requirements for heating system efficiency across all technologies (Braungardt et al., 2021). Additionally, the EU has just proposed including buildings in the EU Emission Trading System (EU ETS) to accelerate decarbonisation. However, that does not mean that targets will be easier to achieve, since many non-monetary and behavioural barriers remain.

Residential heating in Spain has received limited attention from policy-makers. Specifically, Spain has implemented two specific pieces of legislation: (i) a Technical Building Code (CTE), which sets energy-efficiency and renewable energy requirements; and (ii) a Regulation on Thermal Installations in Buildings (RITE), which regulates the energy efficiency of new and existing heating, ventilation and air conditioning (HVAC) systems and water heaters (Collado and Díaz, 2017; Yearwood Travezan et al., 2013). Spain has recently presented its revised national energy and climate plan (NECP, 2020) to help meet EU-wide targets. Additionally, under the EPBD Spain updated its Long Term Strategy for Energy Renovation in the Building Sector in 2020 (ERESEE, 2020). As part of the renovation wave initiative, substantial reductions in energy consumption on heating are expected to result from improved building insulation and renovation of thermal heating systems in 30,000 houses per year on average. However, when it comes to phasing out fossil-fuel heating systems, Spain has no nationwide plan to ban all fossil-fuel boilers. Similar trends can be found in other eastern and southern European countries. Focusing on the targets for increasing the use of renewable sources, the plan is for the share of renewables to increase from 18% in 2020 to 31% in 2030, with biomass as the dominant technology, followed by heat pumps (NECP, 2020). This plan forecasts that the contribution of heat pumps is expected to increase from 629 to 3,523ktoe from 2021 to 2030. However, no forecasts for other renewable technologies are provided.

In that context, the shift towards a decarbonised heating supply calls for energy-efficiency policy instruments (Lowes et al., 2020; Lowes and Woodman, 2020). There is a substantial body of research that analyses the impact of different types of energy-efficiency policy instruments (for a review, see Labandeira et al., 2020). That literature reveals that a policy package can be more effective, efficient and more popular than individual policies (Givoni et al., 2013; Howlett and del Rio, 2015; Kern et al., 2017; Rogge and Reichardt, 2016). Givoni et al. (2013) define a policy package as "a combination of policy measures designed to address one or more policy objectives, created in order to improve the effectiveness of the individual policy measures, and implemented while minimizing possible unintended effects, and/or facilitating interventions' legitimacy and feasibility in order to increase efficiency". Indeed, several studies have argued for the need to combine different policy instruments and proposed policy packages or so–called policy mixes. For example, Bennear and Stavins (2007) focus on the combination of a wide range of policy instruments to regulate energy efficiency in the USA. Fesenfeld (2020) shows that policy packaging can increase support for climate policies. Lehmann (2012) provides a review of economic studies analysing the use of multiple policies to overcome single pollution problems. Focusing on the design of energy-efficiency policies in buildings, Gago et al. (2012) propose a policy package for dealing with the main obstacles to the adoption of energy-efficiency measures in buildings. Knobloch et al. (2019) find that policy mixes are more effective than single policy instruments. Specifically, they show that the combination of a carbon tax with subsidies and procurement policies for renewables is more effective in encouraging a switch to low-carbon technologies. On that basis, our paper contributes to the literature on energy-efficiency policy instrument assessment as well as to the design of policy packages for fostering energy efficiency in heating, which can certainly support effective, efficient policy-making. To that end, the paper proposes a participatory method for the design of policy interventions for the heating transition which factors in the perceptions of different stakeholders.

Policy targets which are technically feasible and socially desirable need to factor in heterogeneity in household behaviour and preferences (e.g. differences in consumer and investment behaviour) (Knobloch et al., 2021). Moreover, the particular characteristics and the barriers to energy-efficiency improvements highlighted in the Introduction suggest that there is a need for intervention from public authorities to design effective energy-efficiency policies. The many factors that policy makers need to consider when undertaking that task include the views of consumers and their potential reactions to policies. By factoring in the perceptions of different stakeholders, this paper seeks to enhance understanding of what works in terms of decarbonisation policies.

3. Methodology

3.1. Fuzzy Cognitive Mapping

The FCM model is used in a similar way to that in Falcone et al. (2019) and Falcone and De Rosa (2020). FCM is a participatory modelling approach employed to determine the behavioural complexity of a system through causal reasoning (Falcone and De Rosa, 2020). FCM also enables stakeholders to show their perceptions and expectations, and policy-makers to advance their understanding of priorities in a transparent manner (Papageorgiou et al., 2009; Sisto et al., 2018). In this sense, scientific literature recognizes that FCM makes for greater public acceptance and effectiveness of policy interventions, because the approach is based on full and equal involvement of all stakeholders (Falcone et al., 2019). The importance of participatory modelling approaches has been recognised in several research fields in terms of helping to find solutions due to its ability to engage stakeholders and incorporate valuable first-hand knowledge such as perceptions and expertise (Falcone and De Rosa, 2020; Özesmi and Özesmi, 2004; Shahvi et al., 2021). There are many participatory modelling techniques, including system dynamics, Bayesian networks, Agent-Based Modelling and Fuzzy Cognitive Mapping (FCM) among others (Voinov and Bousquet, 2010). They are all powerful tools for identifying solutions to a given problem, normally related to supporting decision-making processes, policy design, regulation or management (Penn et al., 2013). We have opted for FCM[1], which has been applied in many different areas such as the food sector (Morone et al., 2019), water management (Shahvi et al., 2021; Solana-Gutiérrez et al., 2017), municipal waste management (Falcone and De Rosa, 2020), urban transformation and resilience (Olazabal and Pascual, 2016), climate change (Reckien, 2014) and the energy transition (Falcone et al., 2019, 2018). FCM offers various advantages over the other participatory research methods mentioned (Table 1). However, it must also be noted that FCM is designed to be a simple, transparent tool, so it has some disadvantages and uncertainties (Table 2).

[1] Due to the complex nature of our case study, i.e. analysing how policy instruments can facilitate the transition towards low-carbon residential heating, we require a method which enables stakeholders' knowledge and perceptions to be integrated, capturing the social, economic, political, environmental and engineering domains (Penn et al., 2013). Furthermore, analysis and considerations of indirect effects between concepts in a system are crucial to provide insight for risk management. In this sense, FCM has been used to understand complex systems more efficiently, making it a useful tool for decision makers. FCM also offers the ability to assess the effects of different policy options through FCM-built scenarios (Jetter and Kok, 2014; Kosko, 1986; Özesmi and Özesmi, 2004).

Table 1. Main advantages of FCM compared to other participatory modelling techniques.

	FCM	Other participatory modelling technique
Advantages	It is applicable even when limited data is available.	System dynamic models They require a variety of empirical datasets (Shahvi et al., 2021)
	Ability to include variables in models which may be not well-defined and to model relationships between variables that are not known with certainty but can be described in degrees such as “a little” or “a lot” (Özesmi and Özesmi, 2004). In other words, FCM uses a combination of network analysis and subjective information from stakeholders to provide an inclusive, fully-complex view.	Bayesian Belief Networks They are typically used to quantitatively assess the map defining conditional probabilities for each variable included in the network and do not handle feedback (Barbrook-Johnson and Penn, 2021; Voinov and Bousquet, 2010).
	It reveals direct and indirect effects between concepts and highlights connections with effects which are less evident, enabling unexpected effects to be identified. This allows for more freedom to represent and analyse sophisticated relationships.	Causal Loop Diagrams They are also used qualitatively to visualise the complexity of a system. They identify potential nodes but ensure a map structure consistent with the method (Barbrook-Johnson and Penn, 2021). In fact, in most participatory modelling techniques stakeholders participate in framing and repeatedly assessing detailed systems produced by expert modellers, whereas FCM engages with stakeholder groups so that they produce models/systems themselves (Penn et al., 2013).

Table 2: Main disadvantages of using FCM.

	FCM
Disadvantages	It does not provide inferential statistical tests or represent temporal dynamics easily, i.e. it cannot model transition behaviour (Özesmi and Özesmi, 2004). As stated by Shahvi et al. (2021), the semi-quantitative values of FCM mean that it is not easy to implement common calibration methods used for quantitative models; instead the steady-state condition (equilibrium condition of the system) is considered as the calibrated form of these systems (Kok, 2009).
	Another perceived drawback of FCM is the abnormal fluctuations of weights that sometimes occur in trials to bring the systems into steady-state mode (Groumpos, 2017).
	The main drawback of FCM-built scenarios lies in the interpretation of causal relationships, due to the complementarity of stories developed by different stakeholders and simulated creative thinking (Kok, 2009).

Considering all these strengths and weaknesses of FCM and despite its not being sufficiently quantitative to facilitate a link with other mathematical models, the value-added of the method arises from the possibility of having a full-complexity view of all stakeholders and perceived effects. This makes the method highly appropriate for this case study in which we wish to incorporate different stakeholder’s perceptions on energy consumption for heating, highlighting connections with non-obvious effects to design effective policies for heating transition.

For the purpose of this analysis, we use four complementary methodological stages (Figure 1). We use three separate maps built up to understand perceptions from different stakeholders regarding the factors that explain heating bills in Spain. These three maps, recently published in López-Bernabé et al. (2020), were drawn up at three focus groups representing different social groups – academics, households and energy experts – in order to capture heterogeneity of behaviour. The second stage involves data processing to produce an aggregate map. In the third stage we conduct a network analysis of that aggregate map. Finally, stage 4 is based on so-called fuzzy inference or policy simulations, characterised by the identification of effective policy packages. In this, we use the FC Mapper tool[2].

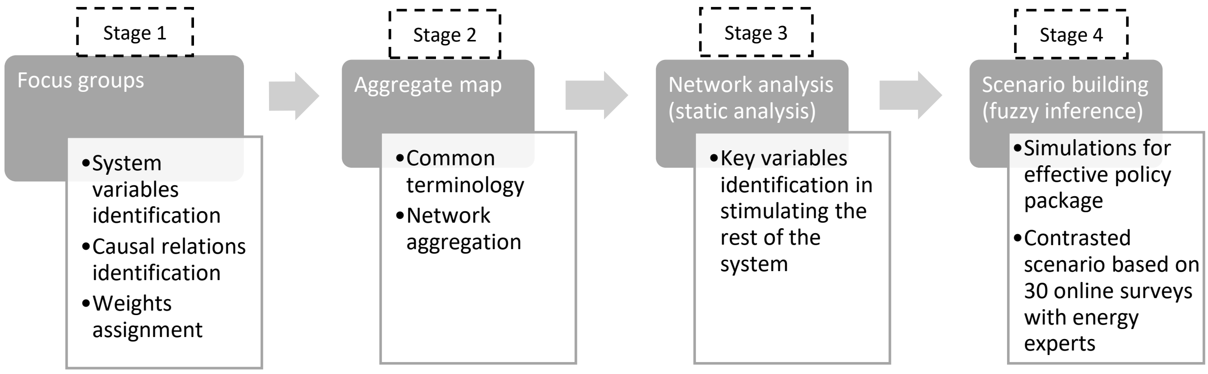

Figure 1. Methodological framework

The four complementary methodological steps used in this approach (stages 1, 2, 3 and 4 in Figure 1) are explained step by step below.

3.2. Stage 1 – Focus groups

Each focus group prepared a map of the determinants for reducing energy consumption for heating and thus heating bills in Spain. The data collection processes for the three separate focus groups are summarised in Table 3.

Table 3. Research process for the three separate maps.

1. Framing research question	The heating case study used in this paper was developed within the framework of ENABLE.EU. Participants received information about the amount of energy consumed for heating in Spain and energy-related greenhouse gas emissions. The research question was designed to elicit the attitudes and opinions of key stakeholders as to what can be done to reduce residential heating bills and how; the obstacles that they face in everyday life; and potential solutions that they

[2]FCMapper is an FCM analysis tool based on MS Excel. It is freeware downloadable from http://www.fcmappers.net/joomla/ (Last accessed May 17, 2021).

			could identify and support. Each focus group session lasted around 2 hours. Note that with the method used in this research participants had to reach a consensus based on their individual opinions. This requires the group of participants to be small so as to reduce misunderstanding and facilitate knowledge exchange.
2.	Three face-to-face focus groups	Academics	Conducted on December 20, 2017 in the city of Bilbao (Spain) with ten participants from the Basque Centre for Climate Change (BC3). Participants were selected on the basis of their expertise in the field of environmental science, climate change and possibly energy.
		Households	Conducted on January 23, 2018 in the city of Bilbao (Spain)with eight participants recruited by the Spanish company CPS. Participants comprised households with different ages, types of residence, numbers of family members and children, locations (urban and rural), levels of income and work statuses (for more details see Appendix A).
		Energy experts	Conducted on January 31, 2018 at the conference of the Spanish Association for Energy Economics (AEEE) in Zaragoza (Spain) with seven participants. This focus group was made up of four researchers and three stakeholders specialising in the field of energy. They were contacted by e-mail.
3.	Data collection process	Identification of system variables (these concepts, also known as nodes, make up the elements or entities of the system analysed)	Step 1. Participants were asked to list and represent the factors or concepts that influenced their heating bills. "What are the basic heating facts, elements or components that influence the amount of your heating bill? (for example, energy price or orientation of the building)"
			Step 2. Participants set out individual actions (measures) which could reduce their heating consumption. "What individual measures could help to reduce your heating bill? (i.e. things or individual actions that can really change your heating consumption, such as lifestyle changes or investment in insulation)"
			Step 3. The participants listed policy measures that the government could implement to bring down heating bills. "What policies could politicians implement to bring down heating bills?"
		Identification of causal relations	Participants were asked to provide a personal opinion as to the possible presence of links between system variables, and a consensus was reached among all the participants. Positive connections indicate that a concept increases (or decreases) in the same direction as others; negative connections indicate opposite directions (i.e. when one increases the other decreases and vice versa). The discussion in the three focus groups was conducted using the same steps indicated in this table, but with some differences. The main difference was that in focus group with energy experts, connections were not centralised via the concept of "heating bill". The main

		reason for this was to create a map with more connections between the different factors mentioned by the participants so as to get more variability in the network.
	Recording weights a posteriori and individually	The weights assigned to causal relations were recorded on an individual basis in order to represent individual heterogeneity relative to the importance assigned to connections between concepts. Specifically, participants were contacted individually one week after the focus group session to assign weights of between 0 and 1 indicating the strength of the connections between two concepts on the maps. Weights close to 0 represent weak connections and those close to 1 represent stronger connections. Recording weights a posteriori and individually enables participants to express their own beliefs regarding links and the importance of the concepts. Of course, this also allows some time to adequately draw the visual map with the required program and minimise potential misunderstandings.
4. Limitations		It can be argued that different focus groups may lead to relatively different findings (e.g. more variability in the variables and weights) but for qualitative analysis it is well documented that the most important factors can be covered in one well-structured focus group (Krueger and Casey, 2008). Based on this, a diversified composition of each focus group profile was preferred to running a second or third focus group with participants with the same diversified profiles.

[1] ENABLE.EU – ENABLE.EU (enable-eu.com)

3.3. Stage 2 - Aggregate map

The three stakeholder maps drawn up by the three different groups – academics, households and energy experts – are combined into one cognitive map. Individual maps offer the experiential knowledge of individuals, capturing many details of specific parts of the system. Homogenised or aggregated maps, on the other hand, offer an integrated view, combining perspectives and therefore better capturing the complexity of an entire system. The combination of different perspectives and views helps to understand how elements from the system may interact and discover cross-sectoral interactions and potential unintended effects (Olazabal et al., 2018a). The weighted average method is used to combine the three separate FCMs into a single collective FCM. This technique consists of averaging numerical values for every given interconnection (Gray et al., 2014). According to Olazabal et al. (2018), the construction of an aggregate map involves several steps. Those steps are detailed in Table 4.

Table 4. Detailed process of constructing an aggregate map.

Steps	Process	Examples
Data treatment	- Maintain original meaning and connotations	- "Outdoor temperature", "Indoor temperature" were all

	- Validate changes with notes/recording and/or with participants.	renamed/reworded as “temperature gradient” - “Children and elderly at home” was renamed as “Vulnerable person” - When a concept was renamed using an antonym the signs of the connections were reversed. - Other concepts in the individual maps were redundant or not well defined, and were therefore deleted (e.g. “renewable energy policies” and “energy saving policies” were left out of the final version because they do not refer to specific policy instruments and have no significant influence on the other concepts in the network). Concepts and links can be removed with no need to change the rest of the system because the effect of each concept antecedent is independent of the effects of the other concept antecedents (Carvalho, 2013).
Homogenisation	- Selection of a consistent terminology across maps. - Choice of level of detail: grouping and ungrouping of concepts. o During this process there were some conflicting links, i.e. links between concepts were checked to avoid inconsistency in relationships and some sign changes were required.	- “Insulation” and “Energy rating houses” were grouped as “Efficiency of dwellings and certificates”. - “Environmental and energy savings information” was ungrouped as “Environmental education and information” and “Education on energy savings” - Additionally, the analysts considered changing specific concepts defined by participants as individual actions to policies (e.g. “Education on energy savings”)
Network aggregation	- Building up the augmented matrix from individual matrices o Define how the weights are averaged when grouping concepts. This applies to individual matrices and to the augmented matrix. o Identify potential incoherencies: two concepts connected with different directions or with different weight signing.	- In our case, weights were generally averaged. Then we built up the augmented matrix using R code, as developed by Olazabal et al. (2018). This code uses individual maps as its source and calculates the final aggregate map. In other words, individual networks were merged with equal impacts and weights on equal links were averaged (Reckien, 2014).

3.4. Stage 3 - Network analysis

To explore the system configuration characterised by the links between variables (i.e. the static analysis), we conducted a network analysis of the aggregate map. To that end, and based on network theory, some key network indices were considered to assess the system architecture and the relevance of certain variables in stimulating the rest of the system (Özesmi and Özesmi, 2003). In our static analysis, relevant information is provided by (i) the centrality index, which denotes the individual importance of one concept relative to others in the network; (ii) the out-degree index, which measures the degree of influence of one concept on others; and (iii) the in-degree index, which measures the degree of dependency of one concept on others in the network.

3.5. Stage 4 - Scenario building

Focusing on policy simulation based on fuzzy inference, FCM enables the answers to "what if" questions to be estimated, e.g. what happens to our system if specific policy instruments change (Carvalho, 2013). The participation of stakeholders in providing their knowledge contributes to the credibility of the scenarios (Kok, 2009). As noted above, results from scenarios can be used to generate new policies because they are built up based on the integrated perspectives of stakeholders (Jetter and Kok, 2014).

Two specific steps can be identified in scenario building and modelling policy interventions: (i) the dynamic behaviour of the network without external influences; and (ii) the policy intervention simulation, i.e. what would happen in the system if different policy instruments were implemented (Falcone and De Rosa, 2020; Lopolito et al., 2020). First, the steady-state vector or system equilibrium is calculated using a specific algorithm (see Appendix B). Steady-state calculations provide the rankings of variables in comparison to each other. To calculate this steady-state, simulations were run by multiplying an initial state vector or activation vector with all variables set to 1 (baseline scenario) by the square weight matrix, whose rows and columns are labelled by the variables of the aggregate map, until the values of the system variables stabilised (Kontogianni and Papageorgiou, 2012). In this study the FCM reached its steady-state in no more than 21 iterations. Steady-state calculation is used to perform a qualitative comparison between variables, i.e. the steady-state value taken by the variable x under the baseline scenario reflects its importance within the system according to people's knowledge (Solana-Gutiérrez et al., 2017). Second, once the steady-state condition is obtained, some of the policy instruments are selected by setting them to their maximum values (normally 1). The simulation is performed by applying the procedure described above, with the difference that only variables representing a specific policy instrument are set to 1 for each iteration step. The effect of the policy instrument analysed is assessed by calculating the percentage of variation between the steady-states of variables representing the policy objectives with and without the policy intervention.

The literature on household energy-efficiency policy instruments (Labandeira et al., 2020; Markandya et al., 2015; Ramos et al., 2015) indicates that policy instruments can be classified into four main categories: (i) command and control instruments (e.g. building codes, minimum energy efficiency requirements); (ii) economic instruments (e.g. tax, subsidies); (iii) information instruments (e.g. certificates, labels, energy audits); and (iv) governance. Table 5 shows the policy instruments of our aggregate map classified according to the literature.

Table 5: Classification of policy instruments.

Command and control instruments	Economic instruments	Information instruments	Governance
Technical standard: Imposition of specific construction standards on new dwellings, or on boilers, making them more energy-efficient. For example, improvements in technical building codes that seek to achieve lower or near- zero energy consumption.	**Subsidies**: Promotion of economic incentives to use renewable energy sources or to purchase energy-efficient systems such as heat pumps.	**Environmental education and information:** Make people who live with you aware of the importance of saving energy, not only for economic reasons but for other environmental issues.	**Governance:** Participants ultimately speak of political will. Specifically, they mention the influence of politicians and the policies that they are willing to implement, including a common understanding of the responsibilities and powers of different institutions and actors, ensuring they are able to deliver outcomes required.
Prosumer: Support renewable energy consumption for residential heating, i.e. highlight the role of renewable energy consumers for heating so that renewable energy consumers can produce, store, consume and sell their own energy to the grid.	**Social bonus:** Discount in power and in energy consumption considering climate differences (see article 15 of Royal Decree 15/2018 in Spain regarding the thermal social bonus) with the need to incorporate requirements for the type of energy source used.	**Education on energy savings**: It is suggested that energy companies could give more information about energy consumption on heating bills. The need for help to understand bills is also mentioned.	
Energy-saving regulation: Compulsory boiler maintenance every 4 years. In this case, combustion improves and performance is higher.	**Taxing bad habits:** A carbon tax could be applied to the use of inefficient boilers. This would increase heating bills. Moreover, this specific tax could lead to more efficient behaviour, for example, investment in insulation.		
Electrification: Heating electrification supported by renewable energy is likely to be a major option for low-carbon heating.	**Taxing fossil fuel used for heating:** Introduce a carbon tax for heating fuels.		
	Tax on consumption: Progressive rates with the aim of penalising energy consumption on heating (the more used, the higher the price).		
	Competition between firms: Rates offered by energy companies. In other words, an option to choose the rate that best suits your consumption habits, i.e. the rate that best suits the consumer's needs, e.g. how much and when they consume.		

Each concept defined as policy instrument in the aggregate map was changed by setting a desirable value for it[3]. In our case, each policy instrument defined in the aggregate map was set at 1 separately. The aim was to identify specific and hidden connections to obtain a better understanding of the application of isolated policy instruments.

3.4.1. Scenario contrasted with energy experts

Then, based on the relevance of the policy packages (identified in Section 2), an additional FCM scenario was built up by simulating several policy instruments together. Data for this additional FCM scenario were obtained from thirty interviews conducted by email in August 2019 with members of the Spanish Association for Energy Economics (AEEE) with expertise in energy efficiency. The aim was to get a comprehensive picture of the application of policy mixes or packages (i.e. combinations of instruments) defined by energy efficiency experts to foster energy efficiency in residential heating. The questionnaire was designed on the basis of the policy instruments mentioned by the participants in the aggregate map drawn up by the three groups (academics, households and energy experts). The main goal of the questionnaire was to compare the policy instruments obtained from the aggregate map with the specific views of people working in the area of energy efficiency. The questions sought to determine which of the policy instruments included in the aggregate map were most important in the view of energy experts, and what other policy instruments could complement them. Accordingly, the questionnaire contained questions on (i) selection of policy instruments; (ii) ranking of policy instruments; and (iii) additional policy instruments to be considered.

4. Results and discussion

4.1. Network analysis

The aggregate map drawn up based on the knowledge of the three stakeholder groups is shown in Figure 2. To visualise our integrated map we used NodeXL Basic[4]. FCMs are converted to square matrices whose elements are every link weight (Özesmi and Özesmi, 2004). Link weights are placed at the intersection cell of each concept shown twice on the matrix, as the cause in the rows and as the effect in the columns (Reckien, 2014).

[3] A variable may be set to 1 for a highly desirable condition or to 0 for a low condition at each iteration step.
[4]NodeXL Basic is a free, open-source template for Microsoft Excel. It is freeware downloadable https://archive.codeplex.com/?p=nodexl from the Social Media Research Foundation https://www.smrfoundation.org/ (Last accessed July 30, 2021).

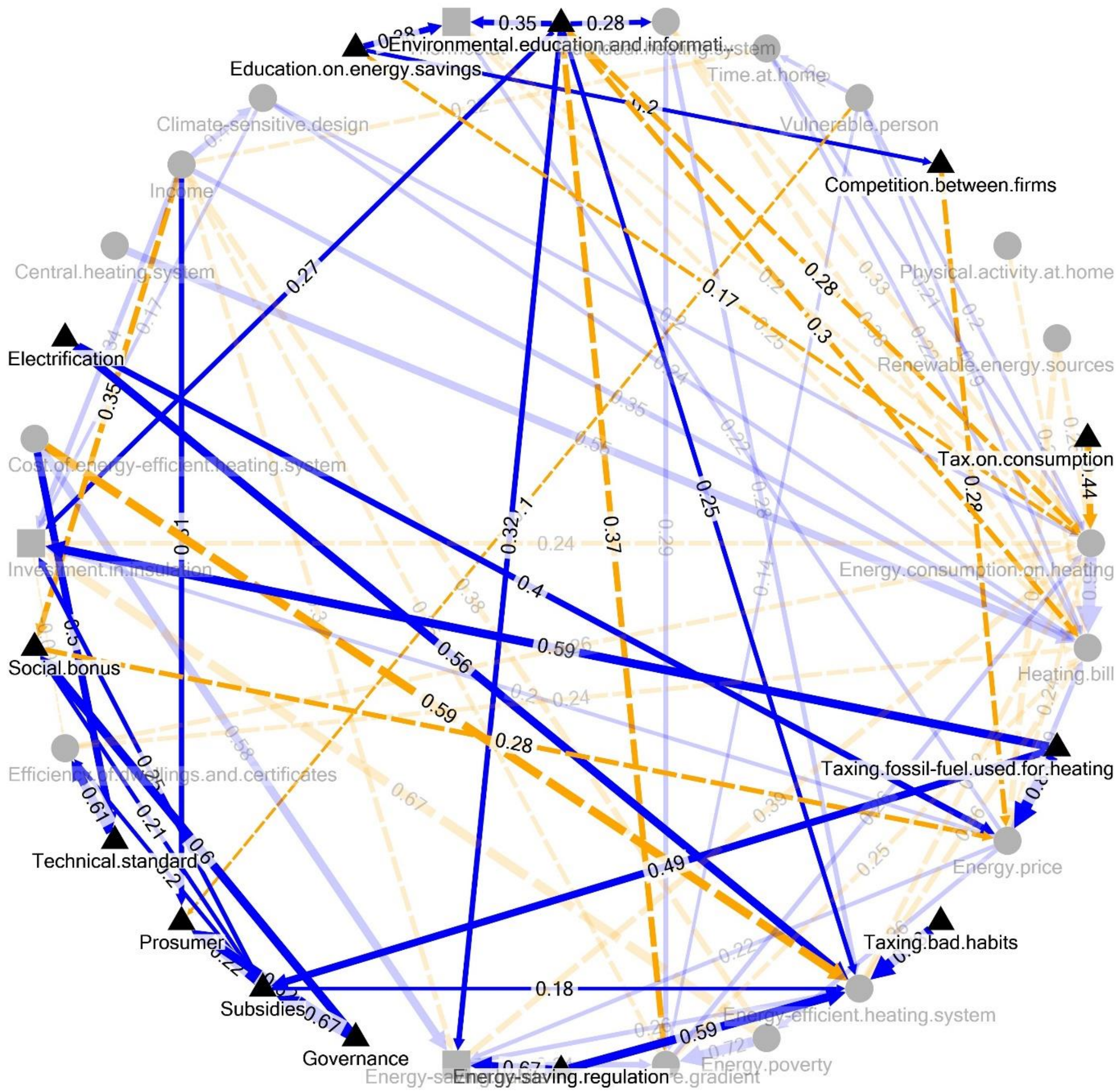

Figure 2: Network aggregated from the maps of the three stakeholder groups (academics, households and energy experts). Blue lines represent positive connections and orange dotted lines negative connections between nodes. Links with policy instruments are highlighted.

The map is composed of 32 nodes (or concepts, C) and 82 connections. Each connection has a weight that represents the strength of the link. Nodes are classified as (i) circles; (ii) squares; and (iii) triangles. Circles represent factors that influence heating bills, i.e. the basic heating facts, elements and components that influence the amount of heating bills. Squares represent individual actions which could reduce heating consumption; and triangles represent policy instruments that the government could implement to reduce heating bills. Arrows show direction and weight (between 1 and 0) according to the strength of the links between connected concepts (Kosko, 1986) derived from the perceptions of participants in the three focus groups. Links can be positive (when one concept increases so does the other) or negative (when one increases, the other decreases) (Kok, 2009).

We analysed three basic indices of FCMs to characterise the role of each concept in our system. The centrality index is based not only on the number of connections but also on their weight. On that basis, the centrality of a concept indicates how closely connected it is to other concepts in the system. The in-degree and out-degree indices measure whether a concept mainly influences or is influenced by the system. This information is reported in Appendix C. According to the stakeholders' knowledge, the top 3 central concepts are "energy consumption on heating", "heating bill" and "energy-efficient heating system". "Energy consumption on heating" and "energy-efficient heating system" both influence and are influenced by the system. This highlights their importance in the structure of the FCM and their role in creating interdependence between the other concepts included on the map. On the other hand, "heating bill" is a receiver concept (zero out-degree), meaning that it has little influence on the system. Focussing on how policy instruments relate to each other and to other nodes, our analysis reveals that the top 3 core policy instruments in the network on the aggregate map are "environmental education and information", "subsidies" and "taxing fossil-fuel used for heating". "Environmental education and information" and "taxing fossil-fuel used for heating" both have a strong influence on the values of other concepts in the system (zero in-degree), i.e. they are both connected to other concepts with a large number of highly weighted connections and are influencers of the system. "Subsidies" are also central to the system, both influencing and being influenced by it.

4.2. Scenario analysis

Applying the fuzzy inference algorithm discussed in subsection 3.4. and Appendix B, the first goal was to explore residential energy consumption on heating according to the integrated perspectives of stakeholders without external disturbances i.e. to calculate the steady-state of the variables as reported in Figure 3. This analysis shows that the most important variables according to the integrated knowledge of stakeholders are "energy-efficient heating systems" and "energy-saving habits", followed by "temperature gradient", "investment in insulation" and "subsidies". The use of "thermostats" or "efficiency of dwellings and certificates" and "social bonuses" are also assumed to play a leading role in promoting the transition of residential heating towards sustainability. Surprisingly, the income is the least significant in the system.

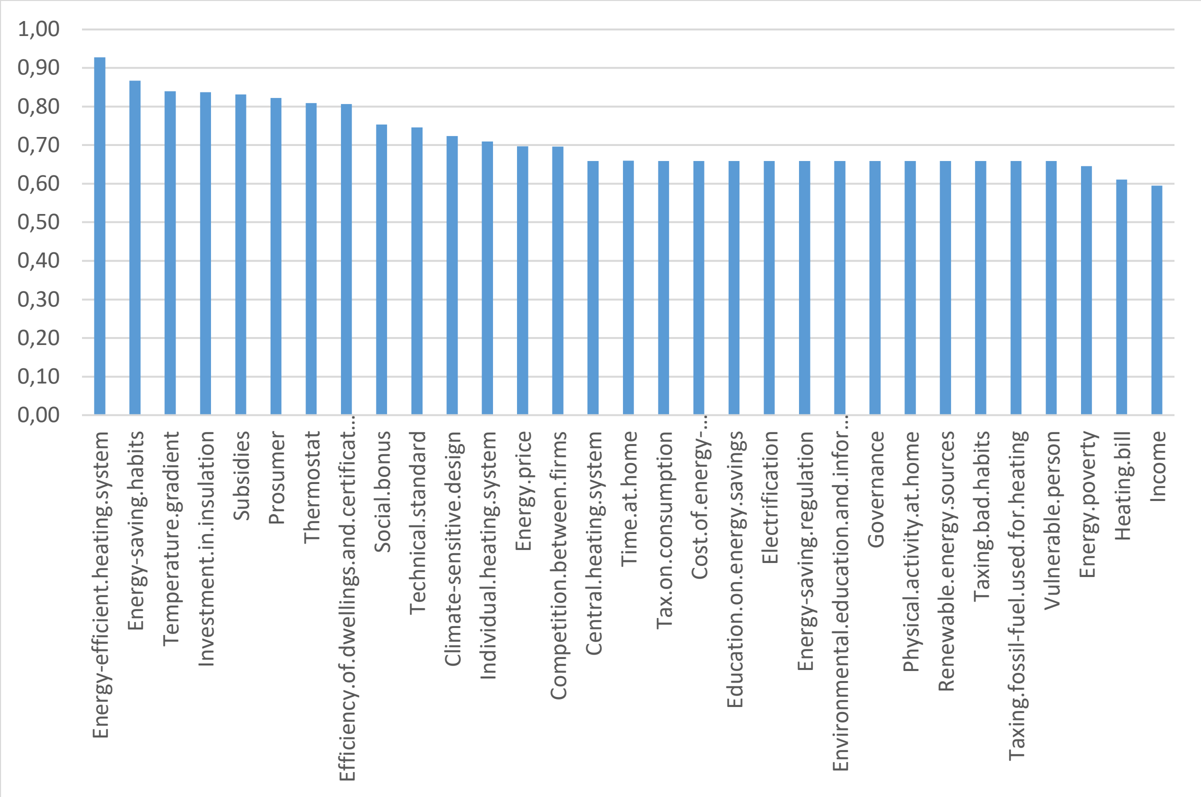

Figure 3. Steady-state values

The next points to be considered are what policies could be implemented to decarbonise residential heating and what would happen if specific policy instruments were reinforced by policy makers. Scenarios were tested by changing the value of each policy instrument defined by each stakeholder group to the highest level of influence. For example, scenario 1 tests the "technical standard" policy instrument, keeping the value of this instrument at one for every iteration phase. Scenario 2 tests the policy instrument called "prosumer", keeping its value at one for every iteration phase. FCM is simulated several times, once for each policy instrument defined by the different stakeholder groups, and the impacts are shown on the aggregate map. The results for each policy instrument in each scenario are shown in Tables 6-11 as the difference between the performance of each instrument and the no-policy case. The sign of the figures shows whether the impact increases (green) or decreases (orange), and the larger the value, the larger the perceived impact. Note that impacts of certain policy instruments on others can also be analysed and are highlighted in grey. These are usually second-order effects which are not always easy to interpret and should therefore be studied with caution.

Table 6: Command and control instruments.

	Command and control instruments			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4

	Technical standard	Prosumer	Energy-saving regulation	Electrification
Efficiency of dwellings and certificates	2.68%	0.00%	0.00%	0.00%
Energy-efficient heating system	0.00%	0.00%	1.36%	1.26%
Energy consumption on heating	-0.12%	0.00%	-0.24%	-0.22%
Energy poverty	0.00%	0.00%	0.00%	0.27%
Energy price	0.00%	0.00%	0.00%	3.49%
Energy-saving habits	0.00%	0.00%	2.67%	0.10%
Heating bill	-0.24%	0.00%	-0.23%	0.10%
Income	0.00%	0.00%	-0.01%	0.00%
Investment in insulation	0.00%	0.00%	0.00%	0.08%
Temperature gradient	0.00%	0.00%	0.14%	0.04%
Thermostat	0.00%	0.00%	0.00%	0.14%

Table 6 shows that "technical standards" are expected to positively impact the efficiency of dwellings and certificates, and hence reduce consumption and heating bills. "Energy-saving regulations" are perceived to produce more energy-efficient heating systems but also to result in better energy-saving habits, which in turn should reduce consumption and heating bills. Finally, "electrification" is expected to produce benefits in regard to energy poverty and promote more efficient systems, but also to increase energy prices and heating bills, according to the stakeholders' knowledge. Curiously, it is expected to increase investments in insulation and temperature gradients as well as thermostats. Temperature gradient and thermostats refer to impacts on lifestyle such as improving the thermal comfort temperature (the difference between indoor and outdoor temperatures) and changing habits by programming thermostats. In this sense, Csutora et al. (2021) test the ability to control indoor temperature and quantitative findings contrasted with the expectations expressed by focus groups, and conclude that culture and established habits play a very important role in determining heating temperatures. According to our analysis, stakeholders believe that the "prosumer" policy instrument has no great impact on other variables.

Table 7. Combination of scenarios 1 and 3.

	Scenario 5
Efficiency of dwellings and certificates	2.68%
Energy-efficient heating system	1.36%
Energy consumption on heating	-0.35%
Energy-saving habits	2.67%
Heating bill	-0.47%
Income	-0.01%
Temperature gradient	0.14%

Stakeholders perceive that a combination of the "energy-saving regulations" and "technical standard" policy instruments (see Table 7) should lead to an increase in energy-efficiency requirements such as efficiency of dwellings and certificates, energy-efficient heating systems and energy-saving habits. Note that the effects of the two policy instruments run in the same direction, so the total effect is reinforced, resulting in a much stronger impact on heating bills and energy consumption.

Table 8: Economic instruments.

	Economic instruments					
	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11
	Subsidies	Social bonus	Taxing bad habits	Taxing fossil-fuel	Tax on consumption	Competition between firms
Efficiency of dwellings and certificates	0.61%	0.00%	0.00%	0.09%	0.00%	0.00%
Energy-efficient heating system	0.22%	0.00%	1.69%	0.04%	0.00%	0.00%
Energy consumption on heating	-0.06%	0.08%	-0.09%	-0.42%	-2.35%	0.10%
Energy poverty	0.00%	-0.15%	0.00%	0.53%	0.00%	-0.18%
Energy price	-0.06%	-1.89%	0.00%	6.88%	0.00%	-2.34%
Energy-saving habits	0.00%	-0.05%	0.00%	0.20%	0.00%	-0.07%
Heating bill	-0.09%	-0.14%	-0.22%	0.46%	-0.68%	-0.17%
Income	0.00%	0.00%	0.00%	-0.01%	0.00%	0.00%
Investment in insulation	0.65%	-0.04%	0.00%	3.11%	0.00%	-0.05%
Prosumer	0.62%	0.00%	0.00%	0.09%	0.00%	0.00%
Social bonus	0.80%	0.00%	0.00%	0.12%	0.00%	0.00%
Subsidies	0.00%	0.00%	0.00%	2.53%	0.00%	0.00%
Temperature gradient	0.00%	-0.02%	0.00%	0.07%	0.00%	-0.02%
Thermostat	0.00%	-0.08%	0.00%	0.27%	0.00%	-0.09%

Table 8 shows that key stakeholders perceive that "subsidies" should result in an increase in the efficiency of dwellings and certificates, energy-efficient heating systems and investment in insulation, but also a drop in energy prices. This is in line with Hesselink and Chappin (2019), who suggest that subsidies help to encourage the adoption of alternative heating technologies. These impacts are thought to be particularly useful in reducing consumption and heating bills, but to a lesser extent than command and control instruments.

Considering the current context of the application of a "social bonus" in Spain, which means a discount in both power and energy consumption, stakeholders perceive that this policy instrument should directly reduce heating bills. In fact, consumers may perceive that their energy consumption is being subsidised so, according to economic theory, one might expect a decrease in energy-saving habits, investment in insulation and use of thermostats.

Focusing on taxation as a policy instrument (scenarios 8, 9 and 10), stakeholders' views suggest that "taxing bad habits" should produce a positive impact on energy-efficient heating systems, thus reducing consumption and heating bills by an amount similar to that for command and control instruments. “Taxing fossil-fuel” is thought to produce greater effects on energy prices than on energy-efficiency improvements (i.e. energy-saving habits or investment in insulation), resulting in an increase in heating bills. The efficiency of heating systems is perceived to not change much. Finally, a “tax on consumption” is expected to decrease consumption substantially (by more than any other policy instrument), thus resulting in the largest reduction in heating bills observed so far.

“Competition between firms” is expected to have a negative impact on energy-saving habits, investment in insulation and the use of thermostats, but is also expected to decrease energy prices and heating bills.

Table 9: Information instruments.

	Information instruments	
	Scenario 12	Scenario 13
	Environmental education and information	Education on energy savings
Climate sensitive design	0.01%	0.00%
Competition between firms	0.00%	1.79%
Energy-efficient heating system	0.66%	0.00%
Energy consumption on heating	-1.95%	-1.01%
Energy poverty	-0.02%	-0.01%
Energy price	0.00%	-0.13%
Energy-saving habits	1.34%	0.00%
Heating bill	-4.20%	-0.48%
Income	0.15%	0.00%
Individual heating system	2.40%	0.00%
Investment in insulation	1.40%	0.00%
Prosumer	0.01%	0.00%
Social bonus	-0.01%	0.00%
Temperature gradient	-1.88%	0.00%
Thermostat	2.07%	2.23%
Time at home	-0.01%	0.00%

Table 9 shows that stakeholders expect “environmental education and information” to produce more energy-efficient heating systems, but also to result in better energy-saving habits, the use of individual rather than central heating systems and investment in insulation and the use of thermostats. This in turn is expected to reduce consumption and heating bills substantially (by more than any other policy instrument considered here), probably because of the combination of the instruments.

“Education on energy saving” is expected to decrease energy prices, consumption and heating bills. It is also expected to result in more competition between firms and an increase in the use of thermostats.

Table 10: Governance instruments.

	Scenario 14
	Governance
Efficiency of dwellings and certificates	0.12%
Energy-efficient heating system	0.04%
Energy poverty	-0.03%
Energy price	-0.34%
Energy-saving habits	-0.01%
Heating bill	-0.04%
Investment in insulation	0.12%
Prosumer	3.40%
Social bonus	4.45%
Subsidies	3.36%

Table 10 shows that governance is expected to positively impact the efficiency of dwellings, promoting efficient systems and investment in insulation. It is also expected to decrease energy prices and heating bills. A negative impact on energy poverty and energy-saving habits is also perceived.

Table 11: This scenario is inspired by energy-efficiency experts from AEEE, based on a survey considering all the policies defined from scenario 1 to scenario 14.

	Scenario 15
Climate-sensitive design	0.01%
Efficiency of dwellings and certificates	3.22%
Energy-efficient heating system	2.05%
Energy heating consumption	-2.64%
Energy poverty	0.51%
Energy price	6.84%
Energy-saving habits	3.89%
Heating bill	-4.22%
Income	0.13%
Individual heating system	2.40%
Investment in insulation	4.67%
Prosumer	0.63%
Social bonus	0.79%
Temperature gradient	-1.67%
Thermostat	2.32%
Time at home	-0.01%

Note: The policy instruments ranked (i) “Energy-saving regulations”; (ii) “Environmental education and information; (iii) “Subsidies”; (iv) “Taxing fossil-fuel used for heating”; and (v) “Technical standards” were set to 1.

When several instruments are combined as proposed by energy experts, most positive impacts are reinforced, as shown in Table 11. This policy package scenario is perceived to increase energy prices but expected to have a large impact on energy-efficiency improvements (efficiency of dwellings and certificates, energy-efficient heating system, investment in insulation and the promotion of individual heating systems). It is also expected to promote energy-saving habits and thus reduce energy consumption on heating and heating bills. This combination is perceived to achieve the largest reduction in energy consumption and heating bills observed for any policy instrument, be it command and control, economic or information-based, according to the stakeholders' perceptions.

4.3. Main findings

Our findings provide several insights for effective policy design in reducing carbon dioxide emissions from residential heating. Stakeholders' perceptions of "technical standards" and "energy-saving regulations" show that they can be expected to have little impact on heating bills and energy consumption. However, combining the two policy instruments (scenario 5) adds together and hence reinforces their effects, resulting in a much stronger impact on heating bills and energy consumption. There is some potential here for correcting market failures due to imperfect information. For example confidence could be created, leading to improvements in investment in energy-efficient heating systems.

Economic policy instruments such as subsidies and social bonuses are perceived to reduce heating bills but to a lesser extent than command and control instruments. Specifically, our results reveal that the "social bonus" is perceived to increase energy consumption on heating, as might be expected according to economic theory. In this regard, Galarraga et al. (2013) show that when subsidies are introduced to reduce energy bills by promoting the purchase of energy-efficient appliances, they may generate a rebound effect in terms of an increase in the total number of appliances and consequently an increase in energy consumption. Other papers also show that perception may play an important role in the acceptability and effectiveness of policies. For instance, Kallbekken et al. (2011, 2010) and Kallbekken and Sælen (2011) find that consumers substantially support subsidies more than taxes, even in situations in which the final outcome of both policies may be similar. This may be because participants expect a subsidy to increase their own payoffs more than a tax, rather than because it is expected to be more effective in changing behaviour (Heres et al., 2017).

Public acceptance of environmental policies is likely to depend on the perceived effectiveness of those policies and on the expected personal gains if they are implemented (Kallbekken and Sælen, 2011). A comparison of scenarios based on tax policy instruments (scenarios 8, 9 and 10) shows that, according to stakeholders' perceptions, a "tax on consumption" is expected to decrease consumption by a substantial amount, which would also result in lower heating bills. This result strongly supports the hypothesis that taxes become significantly more acceptable when there is more complete information

(Heres et al., 2017). In our case, the information revealed by the cognitive map (direct and indirect effects of certain policy instruments on other concepts defined, and connections which have non-obvious effects) increases support for taxes relatively more than support for subsidies.

Stakeholders assign the greatest potential for the heating transition to “environmental education and information”, whose ability to reduce heating bills is the greatest of any of the policy instruments considered here. This is not totally unexpected, although the literature is not always clear with respect to which instruments are more effective. For example, Filippini et al. (2014) find that financial incentives and energy performance standards play an important role in promoting energy-efficiency improvements in the EU residential sector, while informative measures such as labelling and education campaigns show no significant effects. Csutora et al. (2021) also find that providing more meaningful information does not trigger public support. Their findings from contrasting qualitative assumptions with quantitative results show that too little or too much information may result in a failure to save energy, depending on the country (e.g. Hungarians were extremely negative about getting meaningful information compared to other countries). In terms of energy conservation, people prefer practical advice to energy consumption related data. Other approaches point to a central role for informational instruments in different sectors (Falcone and De Rosa, 2020; Ramos et al., 2015). For the specific sector of households, information feedback tools are commonly used and can be effective, but only if they are carefully designed (Ramos et al., 2015).

In scenario 15, which combines several instruments as proposed by energy experts, most positive impacts are reinforced and the reduction obtained in energy consumption and heating bills is the largest of any of the policy scenarios. For example, “subsidies” for replacing fossil-fuel-fired heating systems are perceived to encourage energy-efficiency improvements, promoting energy-efficient heating systems. But this is unlikely to be sufficient according to the stakeholders’ knowledge. Considering the proposed policy package, a “tax focused on fossil-fuel used for heating” is also believed to be needed, i.e. a carbon tax which ensures that costs related to carbon dioxide emissions are assigned individually and not shifted to society in general. An interesting example of the use of public incentives and carbon taxation is the case of Finland, where financial incentives for heating system renovations were promoted for all households, while taxes on fossil fuels continued to rise. This encouraged a switch away from fossil-fuel heating systems towards cleaner systems such as heat pumps (Sovacool and Martiskainen, 2020). Command and control policy instruments and information instruments are also perceived to play a fundamental role in the heating transition. Specifically, “energy saving regulations”, “technical standards” and “environmental education and information” policy instruments are expected to be most effectively addressed under this combination of policy instruments, based on stakeholders’ perceptions.

5. Conclusions and policy implications

As the single largest energy consumer in residential buildings, heating plays an important role in decarbonisation in many countries, and particularly in Spain. The challenge of decarbonising residential heating calls for an effective policy and research response and energy-efficiency policies are key in the transition. However, those policies need to be well designed and implemented as there are many examples of policies which do not produce the expected outcomes. It is thus essential to enhance the understanding of policy impacts and design features. Of course, there are usually differences between the planned design and the implementation features of certain policies for many reasons, and perceptions and/or acceptability of policies can often explain many of those differences. Therefore, taking into consideration the views of stakeholders on what policies should be used and how they can contribute makes for a highly interesting contribution to the analysis of policy interventions; a contribution that complements well the information that economic theory and more traditional economic modelling may provide. Also note that a powerful reason for choosing the heating sector for this analysis is that the residential heating sector has three particular characteristics: (a) heating systems are long-lived; (b) they can be very costly; and (c) a great many agents may be involved in the decision to install and use them.

This paper focuses on residential heating in Spain, but the general arguments used here are likely also to be applicable to other countries with similar characteristics such as Eastern or Southern European countries.

In particular, we analyse the effectiveness of energy-efficiency policies here by incorporating the perceptions of different stakeholders. Understanding stakeholder perceptions of how energy related issues interact provides a very good complement for the more quantitative information traditionally used in policy design, because expectations may significantly affect policy outcomes (i.e. the efficiency and effectiveness of a policy) and because they affect the acceptability of those policies.

This analysis is carried out using the so-called FCM method, a participatory method which captures the diversity of perspectives and opinions that drive heating decarbonisation and has proven very useful in many research areas for the reasons explained above. Here, we integrate the views of three separate groups of stakeholders (academics, households and energy experts) in an attempt to better understand how stakeholders may interact with policy instruments. These same groups were analysed separately in earlier work to obtain a thorough understanding of the differences and similarities in their views. Integrating the views of all three groups to provide a much closer interpretation of reality is the added value that we offer in this paper. This integration also enables us to analyse the expected impact of different policy instruments together in policy packages. Note that a policy package can be more effective, more efficient and more popular than individual policies.

This paper clearly shows that integrating views provides a richer picture of how perceptions may influence the impacts of different policies. Specifically, FCM reveals direct and indirect effects of certain concepts on others and highlights connections which have non-obvious effects that should be considered in designing policy interventions. Bearing in mind this broad range of views from academics, households and energy experts and their perceptions as to effects, we identify the main factors, individual measures and policy instruments that may facilitate the transition in residential heating. FCM is also used for scenario assessment to better understand the strength of policy instruments and interactions between the concepts used to explain the residential heating transition. These outcomes can be very useful tools for policy-making processes.

The specific findings that have emerged from the policy simulation can be summarised as follows. For command and control instruments, when policy instruments comprising energy-saving regulations and technical standards are combined the effects are perceived to be greater than when those instruments are used in isolation. This policy package or policy mix is expected to have a much stronger impact on heating bills and energy consumption. Regarding the choice of economic instruments, a potentially important misconception emerges: consumers seem to underestimate the effectiveness of taxes compared to the effectiveness of subsidies, although the evidence is relatively scarce. Our analysis indicates that when all views are integrated, taxes are expected to be more effective than subsidies, which is indeed what economic theory teaches us. In fact, according to stakeholder views, a direct "tax on consumption" would result in the largest reduction in heating consumption, far greater than that obtained by taxing fossil fuels or other measures. The information revealed by the cognitive map (direct and indirect effects of certain policy instruments on other concepts defined, and connections which have non-obvious effects) increases support for taxes relatively more than it increases support for subsidies. Note also that perceived effectiveness matters as it is an important determinant of acceptability (Kallbekken and Sælen, 2011). In this regard, our results support the idea that the perceived effectiveness of energy policies may be significantly correlated with the acceptability of those policies (Heres et al., 2017).

With regard to information instruments, the greatest potential for the heating transition is expected to lie in "environmental education and information", which can reduce heating bills by more than any other single policy instrument considered here, according to the combined views of the stakeholders groups.

Finally, the combination of several instruments (in so-called policy packages or mixes), as proposed by the energy experts consulted during this research, results in the greatest reduction in energy consumption and heating bills of any policy instrument analysed. This can be attributed to the fact that the effects are added together and hence reinforced, making the impact of a policy package much more evident. In addition, other literature also suggests that policy packages enable more than just one policy target to be addressed.

However, there are several caveats in regard to the work reported this paper. On the one hand, we are using a semi-quantitative methodology whose results need to be handled with care and are not easily extrapolated to other contexts. These results, and the lessons learnt, may be applicable only to very similar contexts and not to countries where heating habits and/or systems are very different from those in Spain. On the other hand, the method is based on perceptions so it does not substitute but rather complements other more analytical and modelling approaches also needed for good policy design. Finally, although great care was put into inviting broad groups of heterogeneous stakeholders, there is always a risk of selection bias when deciding on the specific participants to be invited to each group.

In any event, FCM is a sound, appropriate research methodology for incorporating more qualitative information into traditional policy analysis, and in combination with other approaches it can substantially enhance the understanding of what works, what does not and why. From qualitative research based on focus group discussions, it can be argued that different focus groups may lead to relatively different findings. However, it is well documented that the most important factors can be covered in one well-structured focus group (de Ayala et al., 2020; Krueger and Casey, 2008). The method outlined in this paper can also be used to explore many other policy combinations such as combinations of subsidies and taxes and more complete policy packages with several other instruments together by combining informational, command and control and market instruments. But we believe that the results shown here are a good example of the usefulness of the research technique proposed.

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Appendices

Appendix A: Supporting material for focus groups

Table A.1. Socio-demographic characteristics of participants in focus groups with households.

		Participant							
		1	2	3	4	5	6	7	8
Gender	Male	x	-	-	x	-	x	-	-
	Female	-	x	x	-	x	-	x	x
Education	No formal education qualifications	-	-	-	-	-	-	-	-
	Primary school	x	-	-	-	-	x	x	-
	Secondary school	-	x	-	-	x	-	-	x
	Higher education	-	-	x	x	-	-	-	-
Age	25-44	-	34	42	-	-	-	-	-
	45-64	56	-	-	49	-	45	-	54
	≥65	-	-	-	-	65	-	72	-
Employment status	Unemployed	x	x	-	-	-	x	-	-
	Employed	-	-	x	x	-	-	-	x
	Retired	-	-	-	-	x	-	x	-
Income	<€1,000	-	-	x	-	-	-	-	-
	€1,001-€1,500	x	x	-	-	-	-	-	x
	€1,500-€2,500	-	-	-	-	x	x	x	-
	>€2,500	-	-	-	x	-	-	-	-
Type of dwelling	Owner-occupied	x	-	x	x	x	-	x	x
	Rented	-	x	-	-	-	x	-	-
Municipality	Urban	x	x	x	-	x	x	x	x

	Rural	-	-	-	x	-	-	-	-
Members	No children	-	-	x	-	-	-	-	x
	With children	-	x	-	x	-	x	-	-
	Elderly	x	-	-	-	x	-	x	-
Members of household	1	-	-	-	-	-	-	-	x
	2	-	-	x	-	-	-	x	-
	3	x	x	-	-	x	-	-	-
	4	-	-	-	x	-	x	-	-
	≥5	-	-	-	-	-	-	-	-
Heating system	Central	-	x	x	-	-	-	-	-
	Individual	x	-	-	x	x	-	x	x
	Other	-	-	-	-	-	x	-	-

Table A.2. Characteristics of participants in focus group of academics.

Participant	Gender	Number of dwellings	Type of dwelling	Household size	Municipality	Heating system
1	Male	1	Owner-occupied	2	Urban	Individual-Natural gas
2	Male	1	Owner-occupied	2	Urban	Central-Fossil fuel
3	Male	1	Owner-occupied	4 (2 children)	Urban	Central with individual control-Natural gas
4	Male	1	Owner-occupied	2	Rural	Individual-propane and wood stove
5	Female	1	Owner-occupied	2	Urban	Individual-Natural gas
6	Female	1	Rented	2	Rural	Individual-Natural gas
7	Male	1	Owner-occupied	3 (1 child)	Urban	Individual-Natural gas
8	Male	1	Owner-occupied	5 (3 children)	Urban	Individual-Natural gas-Energy efficient boiler in terms of nitrogen oxides and particulate emissions

Table A.3. Characteristics of participants in focus group of energy experts.

Participant	Gender	Profile	Number of dwellings	Type of dwelling	Household size	Municipality	Heating system

1	Male	Researcher	1	Owner-occupied	2	Urban	Individual-Natural gas
2	Female	Researcher	1	Owner-occupied	3 (1 child)	Urban	Central with individual control-Natural gas
3	Male	Stakeholder specialising in the field of energy	1	Owner-occupied	4 (2 children)	Urban	Central with individual control-Natural gas
4	Male	Stakeholder specialising in the field of energy	2	Owner-occupied	4 (2 children)	Urban Rural	Individual-Natural gas
5	Male	Researcher	1	Owner-occupied	1	Urban	Central-Fossil fuel
6	Male	Researcher	1	Owner-occupied	5 (3 children)	Urban	Individual-Natural gas
7	Male	Stakeholder specialising in the field of energy	1	Owner-occupied	3 (1 child)	Urban	Individual-Natural gas

Appendix B: Fuzzy inference and simulation process

For scenario analysis, a vector of initial values of variables (A) is multiplied by the adjacency matrix of the aggregate FCM using the following function (Kontogianni and Papageorgiou, 2012):

$$A_i^{(k+1)} = f\left(A_i^{(k)} + \sum_{\substack{j=1 \\ j\neq i}}^{n} A_j^{(k)} w_{ji}\right) \quad (1)$$

where $A_i^{(k+1)}$ is the value of concept C_i at simulation step k+1, $A_i^{(k)}$ is the value of concept C_j at step k, w_{ji} is the weight of the interconnection between concept C_j and concept C_i and f is a threshold function commonly used in FCM which normalises the values at each step in the interval [0,1] and its mathematical type is:

$$f = \frac{1}{1+e^{-mx}} \quad (2)$$

where m is a real positive number and x is the value $A_i^{(k)}$at the equilibrium point. A concept is activated by making its vector element 1 or 0 with [1] activated concepts and [0] non-activated concepts. If a concept has an activation value of 0, it does not contribute in the next iteration whereas an activation value of 1 means that it does contribute in the next iteration.

Appendix C: Centrality network analysis.

Here is a list of the 32 concepts consolidated in the aggregated map alongside measures of their centrality. Concepts found to have zero out-degree or zero in-degree are classified as receivers or transmitters, respectively. The concept of in (or out)-degree is the sum of the absolute interaction weights.

Concepts	Concept group	Out-degree	In-degree	Centrality	Concept type
Energy consumption on heating	Factor	0.93	4.00	4.93	
Heating bill	Factor	0.00	4.75	4.75	Receiver
Energy-efficient heating system	Factor	0.68	3.49	4.17	
Energy price	Factor	1.42	2.20	3.62	
Energy-saving habits	Individual action	0.99	2.09	3.08	
Income	Factor	2.65	0.25	2.90	
Investment in insulation	Individual action	0.24	2.48	2.72	
Temperature gradient	Factor	0.76	1.86	2.62	
Environmental education and information	Policy	2.42	0.00	2.42	Transmitter
Subsidies	Policy	1.06	1.16	2.22	
Energy poverty	Factor	1.39	0.64	2.03	
Taxing fossil fuel used for heating	Policy	1.91	0.00	1.91	Transmitter
Governance	Policy	1.89	0.00	1.89	Transmitter
Cost of energy-efficient heating system	Factor	1.67	0.00	1.67	Transmitter
Individual heating system	Factor	1.28	0.28	1.56	
Social bonus	Policy	0.28	1.16	1.44	
Thermostat	Individual action	0.45	0.95	1.40	
Efficiency of dwellings and certificates	Factor	0.50	0.81	1.31	
Energy-saving regulation	Policy	1.26	0.00	1.26	Transmitter
Prosumer	Policy	0.00	1.25	1.25	Receiver
Technical standard	Policy	0.61	0.50	1.11	
Climate-sensitive design	Factor	0.61	0.40	1.01	
Electrification	Policy	0.96	0.00	0.96	Transmitter
Time at home	Individual action	0.43	0.42	0.85	
Vulnerable person	Factor	0.83	0.00	0.83	Transmitter
Taxing bad habits	Policy	0.78	0.00	0.78	Transmitter
Education on energy savings	Policy	0.75	0.00	0.75	Transmitter
Renewable energy sources	Factor	0.67	0.00	0.67	Transmitter
Central heating system	Factor	0.55	0.00	0.55	Transmitter
Competition between firms	Policy	0.28	0.20	0.48	
Tax on consumption	Policy	0.44	0.00	0.44	Transmitter
Physical activity at home	Individual action	0.20	0.00	0.20	Transmitter