# Diffusion of energy-efficient technologies in EU residential buildings

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CHALMERS UNIVERSITY OF TECHNOLOGY
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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# Diffusion of energy-efficient technologies in EU residential buildings

Diffusion av energieffektiva tekniker för bostadshus i EU

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*“Energy and persistence conquer all things”*

Benjamin Franklin

# ABSTRACT

Residential buildings constitute approximately 75% of the European building stock, accounting for around 30% of the EU´s overall energy demand and emissions. They also represent one of the biggest sources of energy saving potential, thus holding a crucial role in achieving EU carbon targets. Technology options to decrease residential building's energy demand to nZEB standards are readily available and, in many cases, economically viable. However, they are not being deployed at the required rate to achieve GHG emission reduction targets. The divergence between the techno-economic potential and actual market behaviour suggests that in the European housing context the economic viability of energy-efficiency technologies (EETs) is not sufficiently acknowledged or appealing to motivate the necessary investments. In order to bridge the energy-efficiency gap and favour the low-carbon transformation of residential buildings in Europe, additional policy measures need to be developed. In a diverse national organisation such as the EU, it is particularly essential to have a national and cross-national scale knowledge to generate an appropriate combination of common and country-specific policies. This knowledge should be based on solid comprehension of the current national and cross-national market conditions affecting the diffusion of EETs.

Against this background, this PhD thesis builds on the research field of technology diffusion with the overall goal of advancing the understanding of the EET adoption in EU residential building stock. In particular, the following research questions are posed: (1) Who are the key decision-makers and persuaders in the technology selection, across building typologies, project types, and EU member states? (2) What are the drivers and barriers for EETs across the EU member states? and (3) What are the EET diffusion gradients across building typologies, project types and EU member states?

To address these research questions while allowing for cross-country comparison of the results, a methodology framework is developed. First, an online survey addressing these research questions is designed and distributed across eight European countries, namely Italy, Spain, Germany, Poland, United Kingdom, France, Belgium, and the Netherlands. The retrieved information is then analysed using a bundle of quantitative methods, specifically social network analysis (SNA), discrete choice modelling, and Chi2 and Cramers V tests.

Results from this study show that the individual level of power and communication varies across the different cases and countries. However, in all instances, multiple stakeholders interact, thereby potentially influencing each other during the technology selection. The potential technology adopters are identified as having the highest power in the decisions, often followed by engineers, architects, and installers. In terms of barriers and drivers, techno-economic arguments are most relevant across most of the geographies and technology solutions, with the exception of electric storage in Germany. Finally, the most often implemented EET measures across the sampled countries and building projects are maintenance of the wall and envelope, new energy-generation systems, and maintenance of the roof or envelope combined with an upgrade of the energy generation system.

Findings from this thesis can contribute to the understanding of EET diffusion in the EU residential building stock. This information, in turn, can support the formulation of evidence-based policies and actions, aimed at stimulating the adoption of these technologies.

**Keywords:** *technology diffusion, empirical evidence, residential building stock, energy efficiency, modelling, decision-making, multiple impacts, European Union.*

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Clara Camarasa

Gothenburg, September 2020

# PUBLICATIONS

## List of publications

This doctoral thesis is based on the following journal papers, referred to as Papers I–VII:

### First author

- **I.** **C. Camarasa**, C. Nägeli, M. Klippel, Y. Ostermeyer, S. Botzler (2019). ”Diffusion of energy efficiency technologies in European residential buildings: A bibliometric analysis”, *Energy and Buildings*. 2019 vol: 202 pp: 109339. doi.org/10.1016/j.enbuild.2019.109339
- **II.** **C. Camarasa**, R. Heiberger, L. Hennes, M. Jakob, Y. Ostermeyer, L. Rosado (2020). ”Key decision-makers and persuaders in the selection of energy-efficient technologies in EU residential buildings”. *Buildings*. 2020, 10(4), 70; doi.org/10.3390/buildings10040070
- **III.** **C. Camarasa**, L. K. Kalahasthi, L. Rosado. (2020). “Drivers and Barriers to energy-efficient technologies (EETs) in residential buildings in the EU”. *Energy and Built Environment.* 2020, 10(4), 70; doi.org/10.3390/buildings10040070
- **IV.** **C. Camarasa**, L. K. Kalahasthi, I. Sánchez-Díaz, L. Rosado, L. Hennes, K. Bienge, I. G. Hamilton (*forthcoming*). “Cross-EU diffusion of energy-efficient measures (EEMs) in residential buildings: An application of discrete choice modelling”. *Submitted to Applied Energy, under review.*
- **V.** **C. Camarasa** (2019). “On the uptake of energy efficiency technologies in European residential buildings”. *Licentiate thesis.* Chalmers University of Technology. Gothenburg, Sweden.

### Second author

- **VI.** C. Nägeli, **C. Camarasa**, M. Jakob, G. Catenazzi, Y. Ostermeyer (2018), “Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks”, *Energy and Buildings*. Vol. 173 pp. 443–460. doi.org/10.1016/j.enbuild.2018.05.055
- **VII.** M. Österbring, **C. Camarasa**, C. Nägeli, L. Thuvander, H. Wallbaum (2018), “Prioritizing deep renovation for housing portfolios”, *Energy and Buildings*. Volume 202. doi.org/10.1016/j.enbuild.2019.109361

Papers I–V constitute the backbone of the PhD storyline. Papers VI and VII complement the storyline and complete its understanding through parallel investigations on EU building stock data generation.

## Author’s contribution

The scope of the contribution for each of the co-authored papers is listed below:

**Papers I–V:** The author of this thesis is responsible for initiating this paper, planning and conducting the research, and performing the analysis. The analysis and writing of the paper were done in close collaboration with the co-authors.

**Paper VI:** The author of this thesis supported the corresponding author in the research design and writing of the paper.

**Paper VII:** The author of this thesis supported the corresponding author in the development of the research design and writing of the paper.

## Other relevant publications

Other authored and co-authored publications, related to energy efficiency in the building stock are listed below. These have been selected as they have been developed along the course of the doctoral thesis and complement some of its findings:

Y. Ostermeyer, **C. Camarasa,** G. Catenazzi, S. Saraf, M. Jakob, C. Naegeli, A. Palacios, U. Reiter, J. Von Geibler, K. Bienge, L. Hennes, E.S. de Baranda, D. Goatman. “Building Market Brief Germany 2019”, ISBN 978-90-827279-2-0.

Y. Ostermeyer, M. Jakob, **C. Camarasa,** G. Catenazzi, S. Saraf, C. Naegeli, A. Palacios, A. Wiszniewski, A. Komerska, D. Goatman. “Building Market Brief Poland 2020”, ISBN 978-90-827279-8-2.

Y. Ostermeyer, **C. Camarasa,** G. Catenazzi, S. Saraf, M. Jakob, C. Naegeli, A. Palacios, U. Reiter, J. I. Hamilton, E.S. de Baranda, D. Goatman. “Building Market Brief United Kingdom 2019’, ISBN 978-90-827279-3-7.

Y. Ostermeyer, **C. Camarasa,** G. Catenazzi, S. Saraf, M. Jakob, C. Naegeli, A. Palacios, U. Reiter, J. Von Geibler, K. Bienge, L. Hennes, E.S. de Baranda, D. Goatman. “Building Market Brief France 2020”, ISBN 978-90-827279-6-8.

Y. Ostermeyer, **C. Camarasa,** G. Catenazzi, S. Saraf, M. Jakob, C. Naegeli, A. Palacios, U. Reiter, J. Von Geibler, K. Bienge, L. Hennes, E.S. de Baranda, D. Goatman, H. Visscher, A. Meijer, A. van den Brom, G. Catenazzi, E. S de Baranda, D. Goatman. “Building Market Brief The Netherlands 2019”, ISBN 978-90-827279-1-3.

M. Jakob, Y. Ostermeyer, C. Naegeli, A. Palacios, **C. Camarasa**, S. Saraf, G. Catenazzi, R. Mahmoud. "Building Market Brief Belgium 2020", ISBN 978-90-827279-1-4.

**C. Camarasa**, et al. (*forthcoming*). Building stock energy forward-looking carbon mitigation scenarios at national and regional level. (Scenario collection for the IPCC Report 6. Chapter: Buildings).

S. Tavares da Silva, et. al. *Energy Efficiency in Developing Countries: Policies and Programmes.* Routledge, 2020. ISBN 978-03-673619-7-6.

J. Reyna, et al. (2020). Developing a common approach for classifying building stock energy models. *Renewable & Sustainable Energy Reviews.*

**C. Camarasa**, H. Wallbaum, E. Roussou, A. Sousanabadi Farahani. (2019), "Relevant Indicators to foster the uptake of EEMs. The European BPOs perspective", *Earth and Environment Conference Proceedings. Sustainable Built Environment (SBE). Temuco, Chile.*

**C. Camarasa**, C. Nägeli, C. Salzer, S. Saraf, Y. Ostermeyer (2015), "Specific Barriers to Massive Scale Energetic Refurbishment for Sample Markets in Europe", *Conference Proceedings. 8th Conference of the International Forum on Urbanism (IFoU). Seoul, South Korea.*

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## ACRONYMS AND NOMENCLATURE

In alphabetical order:

ABM – Agent-based modelling

BE – Belgium

BI – Building intervention

BS – Building stock

BSM – Building stock modelling

BSO – Building Stock Observatory

$CO_2$ – Carbon dioxide

DCM – Discrete choice modelling

DE – Germany

EC – European Commission

EE – Energy efficiency

EED – Energy Efficiency Directive (2012/27/EU)

EEM – Energy-efficiency measure

EET – Energy-efficiency technology

EETM – Energy-efficiency technology measure

ES – Spain

ESCO – Energy supply/utility and energy service company

EoL – End of life

EPBD – Energy Performance of Buildings Directive (revised 2018/844/EU)

EPC - Energy performance certificate

EU – European Union

FR – France

GHG – Greenhouse gas

IEE – Intelligent Energy Europe

IPCC – Intergovernmental Panel on Climate Change

INDC – Intended Nationally Determined Contributions

IT – Italy

MDB – Multi-dwelling building

MNL – Multinomial logit

NL – Netherlands

NLT – Nested logit model

nZEB – Nearly zero energy in building

PL – Poland

RES – Renewable energy sources

RH – Row house

RQ – Research question

SDB – Single-dwelling building

SOTA – State-of-the-art

SI – Slovenia

TH – Terraced house

TABULA – Typology Approach for Building Stock Energy Assessment

UK – United Kingdom

WTP – Willingness to pay

# 1. INTRODUCTION

## 1.1. Motivation and purpose

In the past two centuries, there has been an increase in anthropogenic greenhouse gas (GHG)-producing actions, such as industry, agriculture, and transportation (Matthews, 2018). In 2014, the Intergovernmental Panel on Climate Change (IPCC) reported that scientists were more than 95% certain that global warming is mostly being caused by increasing concentrations of GHGs and other human activities (Brasiliera De Ciências, Japan and Society et. al, 2005). Without action to reduce anthropogenic GHG emissions, global warming is likely to exceed pre-industrialised levels by 2°C. The increase in temperature is already having apparent impacts on the world's landscape and sea levels, resulting in extreme heatwaves, droughts, fires, and flooding, among other effects (IPCC, 2014).

The European Union (EU) acknowledges global warming and is acting accordingly. At the United Nations Climate Conference (COP21) held in December 2015 in Paris, the EU and its 28 member states were one of the first countries to submit an INDC[1], aiming at reducing GHG emissions by 40%[2] by 2030 – in line with the objective of impeding the increase of global warming above 2°C (European Commission, 2015). Achieving the objectives of the Paris Agreement to limit the increase in temperature to less than 1.5–2°C have been translated by the EU to major advances in energy efficiency (EE), as well as the integration of renewable energy sources (RES). This understanding is collected in the 2030 objectives of the EU, which calls for a significant reduction of Europe's energy use by 32.5% compared to the business-as-usual projections (Mathiesen *et al.*, 2019).

In Europe, buildings are responsible for approximately 40% of energy consumption and 36% $CO_2$ emissions and are the single biggest contributor to emissions and energy demand (European Commission, 2019b). Furthermore, about 35% of the building stock is over 50 years

[1] Intended Nationally Determined Contributions (INDCs).
[2] Relative to 1990 levels.

old and more than 75% is energy inefficient. Buildings are, in this way, the largest potential targets for improving EE and mitigating GHG emissions and are mostly untapped.

In view of this situation, the European Commission is determined to upgrade the energy performance of the building stock and has appointed two main task forces to support this assignment: (1) the Energy Efficiency Directive (EED) (2012/27/EU) and (2) the Energy Performance of Buildings Directive (EPBD) (revised 2018/844/EU) (European Commission, 2015; European Commission, 2018). The EED establishes a set of binding measures to help the EU reach its 20% energy-efficiency target by 2020. Alongside the EED, the EPBD covers a broad range of policies and measures to help national EU governments boost the energy performance of buildings and improve the existing building stock. These include energy-performance certification of buildings, inspection regimes for boilers and air-conditioning plants, and requirements for new buildings to be nearly zero-energy (nZEB). Given that most of the buildings that will exist in the year 2050 are already built, many of these measures are focused on renovation (European Commission, 2019a). For instance, Article 4 of the EED requires that member states "establish a long-term strategy for mobilising investment in the renovation of the national stock of residential and commercial buildings, both public and private".

Technology options to decrease a building's energy demand (even up to nZEB standards) are readily available and, in many cases, economically viable (McKinsey&Company, 2010; D'Agostino and Parker, 2018). The promising performance and economic potential of these technologies have also been acknowledged in residential buildings at the EU level (Hermelink *et al.*, 2013; Kranzl *et al.*, 2014; BPIE, 2015). However, energy-efficiency measures (EEMs) are not being implemented at the rate required to achieve the Paris Agreement commitments. Annual new construction rates in the residential sector are still around 1%. In terms of retrofit activities, an average of 0.4–1.2% of the EU residential stock is renovated each year

(Economidou *et al.*, 2011), of which less than 5% reaches nZEB standards [3] (Groezinger *et al.*, 2014). This implies that, despite their availability and economic viability, energy-efficient technologies (EETs) are not being deployed at the rate required to meet the EU's carbon reduction targets. The divergence between the techno-economic potential and actual market behaviour has been coined as the "energy efficiency gap" or "energy paradox" and implies that non-technical hurdles are preventing the large-scale diffusion of these solutions (Jakob, 2007). The energy-efficiency gap also suggests that, in the European housing context, the economic viability of EETs – specifically the cost of potential energy savings (commonly considered being the only financial benefit) – is not sufficiently acknowledged or appealing to motivate the necessary investments (Popescu *et al.*, 2012).

In order to bridge the energy-efficiency gap and favour the low-carbon transformation of residential buildings in the EU, national policy measures need to be (further) developed. This requires a solid comprehension of the current national market structures and dynamics, especially those related to the deployment of EETs (Perrels, 2001). In such a way, by understanding the diffusion of EE innovations in the residential sector, it is possible to accelerate the technology adoption process through more effectively designed programmes, demonstration projects, channels of distribution, marketing strategies, and policy incentives (Koebel *et al.*, 2004). In a diverse national organisation such as the EU, it is particularly essential to identify country- and cross-scale knowledge to generate an appropriate combination of common and country-specific policies (European Commission, 2019a).

In scientific terms, the understanding of technology dissemination – along with its attitude-based conditions and dynamics – has typically been addressed through (1) the collection and analysis of building stock information, and/or (2) the understanding of decision-making processes behind its adoption. In the EU residential sector, there are many examples of scientific studies on providing empirical and/or modelled evidence of the actions and

[3] The exact percentage varies as of each EU member state

underlying factors of household's adoption (Atkinson, Jackson and Mullings-Smith, 2009; Calì *et al.*, 2016). However, due to the diversity of scopes, variables, and approaches among the studies, comparing findings across these countries is not always possible: an inconsistency which, in turn, hinders a solid pan-European overview of this field (European Commission, 2018a).

Against this background, the motivation of this thesis is to contribute to the scientific ground in the field of diffusion of EET in the European residential building stock. More specifically it intends to answer the (1) how, (2) what – in terms of the gradients [4]of EET are spread in the residential building sector, and (3) why, placing special emphasis on how this might differ across the different EU member states.

Such an analysis can contribute to the understanding of EET diffusion in general and the formulation of common and country-specific policies aimed at stimulating and accelerating the adoption of these systems in particular.

## 1.2. Objective and research questions

The goal of this thesis is to advance the understanding of EET diffusion in EU residential buildings. This goal is divided into three main objectives: (1) increase the empirical evidence of this topic, (2) characterise and quantify the most relevant components, and (3) enable cross-country comparison of the results.

This thesis aims to answer four main RQs: a preliminary one, related to the state of research (RQi, the results of which are presented in Section "2. STATE OF RESEARCH" and frame the formulation of RQI-III); followed by three more RQs, which outline the core of this thesis' contribution (RQ I–III).

[4] An increase or decrease in the magnitude of a EETs observed in passing from one point to another (i.e. from one EU country to another).

RQs I–III are formulated and structured following the definition of technology diffusion theories: technology diffusion or adoption theories seek to explain *(1)* ***how****, (2)* ***why****, and (3)* ***with what gradients*** *or rates new ideas and technologies are spread.* This overarching definition has been tailored to the EU residential sector, based on the identified research gaps and needs:

*(1)* ***How*** *are the technologies spreading?*

**I. Who are the key decision-makers and persuaders in the technology selection, across building typologies, project types, and EU member states?**

***(2) Why*** *are the technologies spreading?*

**II. What are the drivers and barriers for EETs across the EU member states?**

*(3)* ***With what gradients*** *are the technologies spreading?*

**III. What are the EET diffusion gradients across building typologies, project types and EU member states?**

## 1.3. Scope and limitations

In line with the RQs, the following system boundaries are established:

**EU member states**

This thesis sets its system boundary in the EU28 and its member states[5]. Thus, any other country or region beyond the EU28 lies out of the scope of the study.

**Residential buildings**

Due to the predominant role of the residential stock in the EU context (around 75%) and larger data availability (Marina Economidou *et al*., 2011), this thesis focuses on residential stock, thus excluding non-residential buildings from the analysis.

**Energy efficiency on a building level**

In the EED Art. 2 (4), EE is defined as "the ratio of output or performance, service, good or energy, to the input of energy" (European Commission, 2012). While this definition is adopted

[5] The United Kingdom (UK) is included in the study as for the time it was conducted the UK remained as a full member of the EU and rights and obligations continued to fully apply in and to the country.

in this thesis, it is sensitive to the description according to its system boundaries: the building and its immediate site. Thus, further urban spaces or functions, such as distribution networks or energy sources, are excluded from the scope of this investigation.

**Energy-efficient technologies (EETs)**

The focus of this study is EETs, defined as an energy-using appliance, equipment, or system whose implementation results in reduced energy use while maintaining a comparable or higher level of service. At present, in the European residential building context, EET choices are mostly based on proven science rather than on the radical improvement or innovation of future technologies. Some knowledge acquired from innovations is considered in this thesis[6], yet the focus is established in those solutions outlined as having reached the production rank 8 (first-of-kind commercial system) and 9 (full commercial application) in the technology readiness level (TRL) scale (European Commission, 2016). The complete list of building components and technologies addressed in this dissertation can be accessed in Appendix V.

**Building's life cycle**

In terms of the building's life cycle, all phases related to the design, construction, and use of the building are taken into consideration in this study. Accordingly, actions related to its end of life (EoL, such as demolition or waste management), or technology generation (raw material extraction or acquisition, processing and manufacture) are excluded from the analysis.

**All stakeholders involved in the value chain**

Diffusion of an innovation can be analysed at different levels. From a macro level, the diffusion of technology can be investigated by using the "*systems of innovation*" concept. According to this concept, it is important to analyse the whole system, including the role of supply- and demand-side actors, institutions, as well as the technology itself (Edquist and Johnson, 1997). Based on this principle, all stakeholders (i.e. actors with a vested interest in

[6] During the data collection, survey respondents were asked on what innovations (beyond the listed ones) they considered to be as relevant as EE in their context.

the project) involved in the building value chain (including technology suppliers) were included in the data collection.

## 1.4. Structure of the dissertation

This dissertation consists of a summary and four research papers, each addressing one RQ. The first paper characterises the current state-of-the-art in the field (RQi). The remaining three papers, deemed as the core contribution of this thesis, focus on a specific element of technology diffusion of EEMs in EU residential buildings (RQ I–III). All of the papers have been peer-reviewed and published in a scientific periodical[7]. The thesis is, hence, structured into the following chapters:

Chapter 2, in which the state of research is characterised and narrowed down to specific research topics. The goal of this chapter is two-fold: first, to better understand the scientific base in the diffusion of energy-efficiency technology for the European residential BS; and second, to define a specific niche and field of study for the PhD project. The content contained in this chapter is a synthesis of the information contained in Paper I.

Chapter 3 describes the research tools and methods utilised in the study. These are adapted in each RQ and subsequent paper: (1) the literature review method (Paper I; RQ i); (2) the data collection method, (common for Papers II–IV; RQ I–III); and (3) the data analysis methods, distinct for each RQ and respective journal paper.

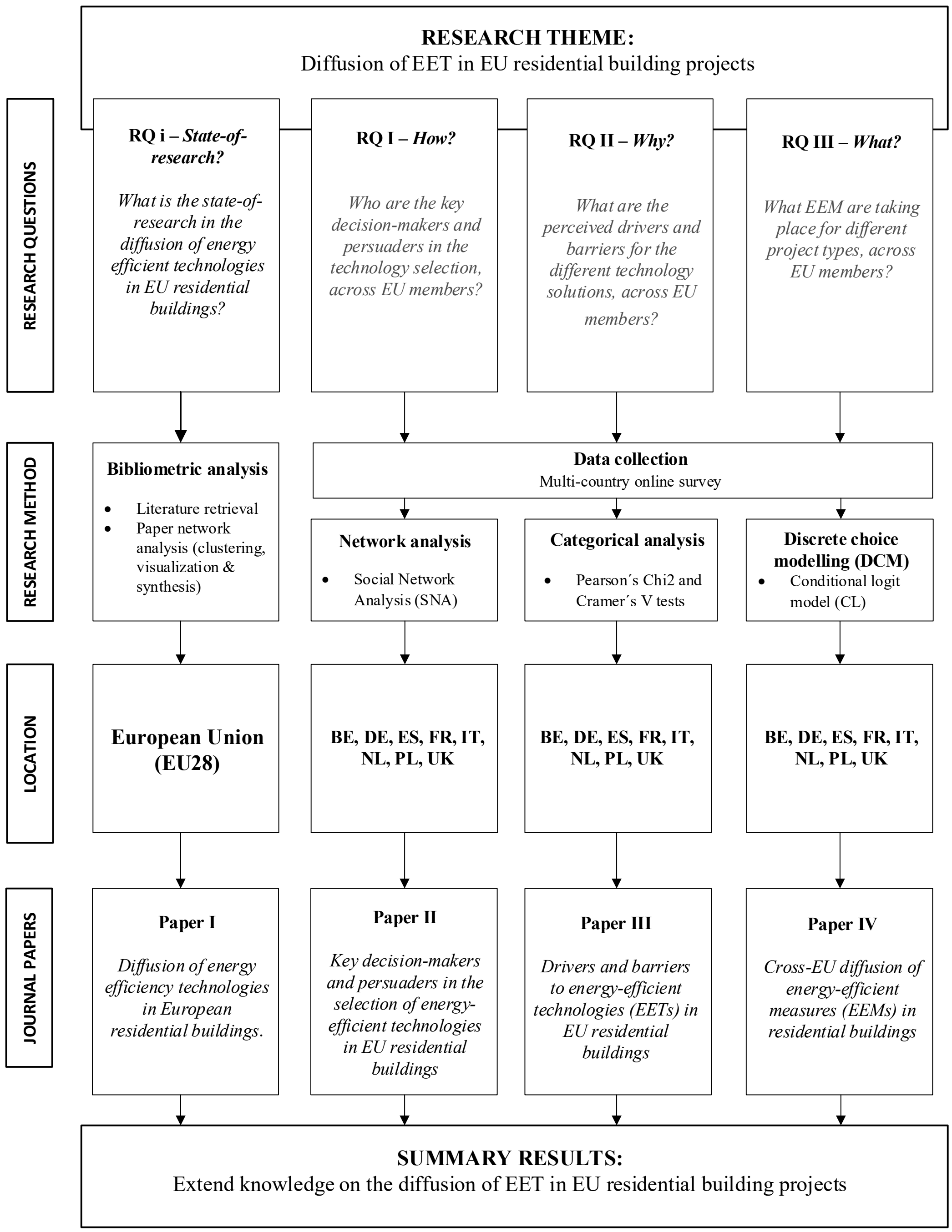
A synthesis of the key findings is presented in Chapter 4, broken down by each RQ.

Chapter 5 expresses future research, outside the scope of the PhD, as well as its connection to other research fields.

The overview of RQs, methods, location, and journal papers are presented in Figure 1.

[7] Paper IV is currently under review.

Figure 1. Overview of RQs, methods and journal papers presented in this thesis. Source: Own elaboration.



# 2. STATE OF RESEARCH

To answer to the initial research question of this thesis (RQi, "What is the state of research in the diffusion of EET in EU residential buildings?"), a bibliometric analysis was conducted leading to the journal paper (Paper I) "Diffusion of energy-efficiency technologies in European residential buildings". A synthesis of the results from Paper I are presented in this section. The complete document can be accessed in Annex I. Further details of the methodology are available in Chapter 3 "Research methods and tools".

This chapter is divided into three sections: the first and second address technology diffusion in residential energy use and EU residential building-stock data, respectively. The third section synthesises the findings, identifies the research gaps, and outlines the niche of this thesis.

## 2.1. Technology diffusion in residential energy use

### 2.1.1. Theoretical frameworks of technology diffusion in residential energy use

To contextualise the theoretical framework in which the content of this thesis is embedded (i.e. technology diffusion), it is necessary to revise decision-making models in the field of residential energy use. According to Wilson et al., in the field of residential energy use, decision-making models can be divided into five main disciplinary approaches according to the scope and focus of the model used: (1) conventional economics, based on a utility-maximisation decision model of consistent and fixed preferences; (2) behavioural economics, which considers the widely varying decision heuristics and context-dependent preferences; (3) technology diffusion, which takes an attitude-based perspective on the evaluation of technologies and the consequences this has on adoption; (4) social psychology, which studies the interacting physiological and contextual variables around the technology; and (5) sociology, which investigates the socio-technical construction of the demand (Wilson and Dowlatabadi, 2007). The overarching label "Applied behavioural research on energy efficiency" identifies a body of research mainly concerned with empirical findings on behaviour and decision-making, especially in a domestic context, and with how this data can be implemented in policy or intervention design (Wilson, Crane and Chryssochoidis, 2015).

This label covers conventional economics, behavioural economics, technology diffusion, and social psychology (Wilson, Crane and Chryssochoidis, 2015). Thus, sociology theories typically exclude behavioural aspects from their analysis and are thus out of the boundaries of applied behavioural research on EE.

The comparison of these disciplinary approaches in relation to their research methods, their dependent variables, and their implications are presented in Table 1.

Table 1. Disciplinary approaches to decision-making in the context of residential energy use. Adapted from (Wilson and Dowlatabadi, 2007).

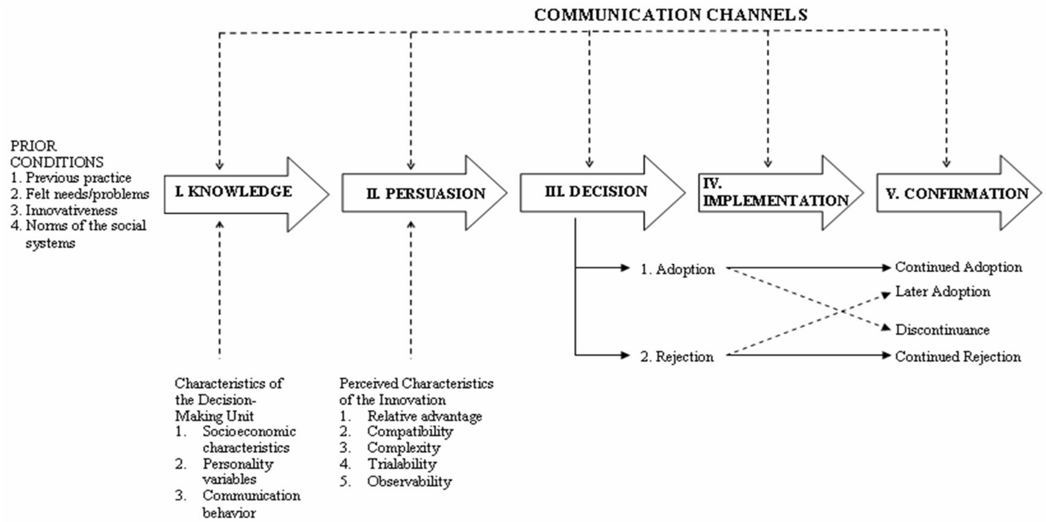
| | **Applied behavioural research on EE** | | | | |
|---|---|---|---|---|---|
| **Main features** | **Conventional economics** | **Behavioural economics** | **Technology diffusion** | **Social psychology** | **Sociology** |
| **Decision model** | Utility-maximisation based on fixed and consistent preferences | Widely varying decision heuristics and context-dependent preferences | Attitude-based evaluation of technologies and consequences on adoption | Interacting psychology and contextual variables | Socio-technical construction of demand |
| **Decision scale** | Individual | Individual | Individual/social | Individual/social | Social |
| **Main dependent variables** | Costs and benefits of outcomes and their respective weighting | Aspects of the decision frame, context, and elicitation method, as well as outcomes | Adopter role in social networks, communication channels, technology attributes, and leadership of adopter | Values, attitudes and norms, socio-demographic economic incentives, skills, capabilities, and resources | Social, cultural and technical determinants of energy demand embedded in routine behaviour |

In this way, technology diffusion theories are one of the five disciplinary approaches within the overarching theoretical framework “Applied behavioural research on energy efficiency". Adoption or technology-diffusion theories seek to explain how, why, as well as with what gradient and rate new ideas and technologies are spread (or not, depending on the case) (Rao and Kishore, 2009). Professor Rogers popularised the concept in his book "Diffusion of Innovations", where he argues that diffusion is the process by which an innovation[8] is communicated over time among the participants in a social system (Rogers, 1983). Diffusion of an innovation can be analysed at different levels. At the macro level, the diffusion of a single technology can be investigated by using the *systems of innovation* concept. Concerning this concept, it is important to analyse the whole system, including the role of supply- and demand-side actors, institutions, and the technology itself (Edquist and Johnson, 1997).

Rogers describes the technology selection process through his innovation-decision model (Figure 2). In this model, he describes five stages that potential innovation adopters typically traverse when deciding on an innovation. The initial phase of an adoption-decision procedure is the need for a new technology or method. After establishing this need, potential adopters will plan to install a new system. In the third stage, homeowners will gather data on technology solutions from different mass media and interpersonal sources. According to the information collected, they will compare the available systems and choose one with greater advantages. However, the necessity for a novel system and its perceived advantages are further shaped by a complex range of both internal (e.g. socioeconomic) and external (e.g. government aid and marketing campaigns) factors to the potential adopter.

[8] In this context, innovations are defined broadly as "an idea, practice or technology perceived as new" (Rogers, 1983). Due to the low uptake of some of these solutions across most EU countries, this term is deemed as adequate within this study.

Figure 2. A Model of Five Stages in the Innovation-Decision Process. Source: (Rogers, 1983).




### 2.1.2. Technology diffusion in European residential buildings

With regards to residential energy use in the EU – due to the profound heterogeneity in the socioeconomic contexts across countries, as well as the major challenge of collecting building stock data – most studies focus on a single country or region (Ulterino, 2014). In the UK, for instance, Hamilton et al. investigate the combination of measures that have been installed according to key neighbourhoods and found that adoption was higher among low-income housing that reflected government support, but that proportional energy savings were greater among high-income households (Hamilton *et al.*, 2016). In parallel, Caird et al. surveyed consumers' reasons for adoption, and non-adoption, of energy-efficiency measures and renewable energy systems and their experiences of using these technologies. The results of this study showed that adopters typically adopted these technologies to save energy, money, and the environment, which many considered they achieved despite rebound effects (Caird, Roy and Herring, 2008). In an earlier study conducted in Ireland, Scott calculated the adoption of attic and water-cylinder insulation as well as low-energy light bulbs in Irish households and showed that the reasons for adoption were somewhat similar to those found by Brechling and Smith for the United Kingdom: information, potential saving, and access to credit and transactions costs, among others (Scott, 1997). O'Doherty et al. centred their research on energy-using appliances and their energy-saving features. They concluded that important features affecting the use of energy efficient appliances included location, value, and dwelling type, while household features such as income, age, period of residency, social status, and tenure type are also important (O'Doherty, Lyons and Tol, 2008). In the Netherlands, Poortinga et al. studied values and environmental concerns and included an extensive list of technological measures and behavioural practices associated with household energy use. Their results suggest that using only attitudinal variables, such as values, may be too limited to explain all types of environmental behaviour (Poortinga, Steg and Vlek, 2004). In Germany, Michelsen et al. explored the potential advantages of housing companies' being of a larger size – specifically, economies of scale, economies of scope, and institutional learning in thermal upgrades of residential housing – demonstrating that large housing companies far outperform private landlords in high-effort refurbishment projects. In contrast, private landlords appear to have advantages in low-effort, incremental refurbishment activities (Michelsen, Rosenschon and Schulz, 2015). Similarly, Achtnicht et al. studied factors influencing German home owners' preferences regarding energy retrofits based on a survey of more than 400 owner-occupiers of single-family detached, semi-detached, and row houses: house owners for whom there was a favourable opportunity were more likely to undertake energy retrofit activities (Achtnicht and Madlener, 2014). Kesternich et al. derived the factors which increase the willingness to pay (WTP) for EE in the case of an upcoming move and found that the WTP is not mainly determined by socioeconomic attributes such as household income or formal education but rather by environmental concerns and energy awareness (Kesternich, 2010). Michelsen et al. explored motivational factors influencing the homeowners' decisions on residential heating systems in Germany and was able to demonstrate that adoption motivations can be grouped along six dimensions: (1) cost aspects, (2) general attitude towards the residential heating systems, (3) government grant, (4) reactions to external threats (i.e., environmental or energy supply security considerations), (5) comfort considerations, and (6) influence of peers (Michelsen and Madlener, 2013). In Sweden, Mahapatra et al. analysed the uptake of heating systems, identifying that the government investment subsidy was important for conversion from a resistance heater but not from an oil boiler (Mahapatra and Gustavsson, 2008). Nair et al. considered several thermal-energy investments as behavioural practices related to electricity and thermal-energy use for owners of detached houses, concluding that personal attributes such as income, education, and age, and contextual factors including the age of the house, thermal discomfort, past investment, and perceived energy cost, influence homeowners' preference for a particular type of energy-efficiency measure (Nair, Gustavsson and Mahapatra, 2010). Ek et al. focused on the role of information in energy conservation behaviour among Swedish households. Their results indicate that both costs and attitudes – in particular environmental motives – are important. (Ek and Sôderholm, 2018).

Another method to study decision-making processes in EET diffusion is through agent-based modelling (ABM). ABM is a class of computational models for simulating the actions and interactions of autonomous agents (both individual and collective entities, such as organisations or groups). It has often been used as a tool to represent the complexities of energy demand in the building sector, such as those caused by social interactions and spatial constraints (Gargiul*o et al*, 2010). For instance, Stephan et al. used ABM to understand how social network interactions can help stakeholders with different characteristics to prioritise their values relating to cost awareness, energy-saving and organisational performance (Stephan *et al.*, 2015). Knoeri et al. studied construction stakeholders' decisions regarding recycled mineral construction materials in Switzerland (Knoeri *et al.*, 2014). Moglia et al. applied ABM to several scenarios with policies aimed at increasing the adoption of solar hot-water systems (Moglia and James, 2018). However, to date, studies have focused on a single technology or geography.

## 2.2. Building-stock data in the EU

Beyond the decision-making testimony, an inevitable step in describing EET diffusion is understanding the current conditions of the building stock (BS) along with the EEMs being implemented.

One of the largest EU initiatives to characterise building typologies across European countries is the IEE (Intelligent Energy Europe) projects TABULA ("Typology Approach for Building Stock Energy Assessment") and EPISCOPE (Ballarini *et al.*, 2011). In TABULA, each typology is defined by building types with specific parameters. In EPISCOPE, residential building typologies for 10 European countries were further developed and new typologies for 6 more countries were elaborated. In this context, the common typology scheme was extended to include showcases of new buildings exemplifying energy performance levels meeting current national requirements or, as alternatives, more ambitious standards up to nZEB level. Similarly, Meijer et al. developed a pan-European study comparing European residential BSs as well as performance, renovation, and policy opportunities (Meijer, Itard and Sunikka-Blank, 2010). In parallel to the scientific publications, another of the consulted databases on BS data was the Building Stock Observatory (EU BSO). The EU BSO is the EU's main initiative generating and collecting data on buildings, as well as their EE status across European member states (European Commission, 2020). Since 2014, it has gathered information on the BS characteristics, including energy consumption, technical systems, energy certification schemes, financing vehicles for building renovations, as well as other socioeconomic aspects such as energy poverty. The EU BSO offers a publicly available database, a data-mapper, and various topic-specific factsheets. However, the database is currently fragmented and incomplete. Nearly 86% of all intended data points are presently missing. For several EU members, factual evidence of what technology measures are implemented, at what rate, and in which settings is completely unavailable for some or all typologies. In addition, no consistent methodology exists to obtain the existing data points, which leads to questions on the consistency of the present information as well as the cross-country comparability of the available indicators.

### 2.2.1 Building-stock modelling

The lack of BS data can be partially attributed to the absence of monitoring of past and present construction and retrofit measures. This data deficiency, however, can be bridged through the use of building-stock modelling (BSM). BSM is an emerging field which aims to assess the development of larger BSs by a variety of methods. BSMs can also be applied to describe pathways for reducing GHG emissions and energy demand by considering the conflicts and synergies between various strategies and technological solutions at a stock level. Papers VI and VII of this thesis are examples of how BSM can be used not only to bridge the lack of data but even assess the BS energy demand and emissions, as well as trace tailored strategies and technological solutions (Kavgic *et al.*, 2010; Mastrucci *et al.*, 2017; Nägeli *et al.*, 2018).

## 2.3. Research gaps and needs

As mentioned above, at the macro level, the diffusion of technologies can be investigated by analysing the whole system, including the role of all stakeholders and institutions (Edquist and Johnson, 1997). In the European residential context, however, due to the broad scope and complexity, most studies focus on a specific technology (or group of technologies, e.g. heating systems), building typology (e.g. single-family houses), or project types (e.g. retrofit projects). In terms of the project type, the majority of the papers address retrofit activities, echoing the emphasis of the EU in upgrading the existing BS (Abreu, Oliveira and Lopes, 2017; Hrovatin and Zorić, 2018). As for the building typology, many focus on single-family houses, identified as the typology hosting the highest energy-efficiency potential in many EU countries (Kragh and Rose, 2011; Mahapatra *et al.*, 2013; Mortensen, Heiselberg and Knudstrup, 2016). An example of this is the analysis of the effect of energy performance information on consumer adoption developed by (Lee, Lee and Lim, 2018).

Inasmuch as technology diffusion theories stress the role of the social system in the process, it is noteworthy that most of the studies within the European residential context focus on investigating this phenomenon from a single-actor perspective. This is typically the demand-side actor, namely the potential technology adopter, such as the homeowner or the housing association (Banfi *et al.*, 2008; Gan *et al.*, 2015; European Commission, 2018b).

At the geographical level, most of the retrieved papers cover a single country or region (Achtnicht, 2011; Kragh and Rose, 2011; Mills and Schleich, 2012). Hence, comparing the findings across these countries is not always possible due to the diversity of scopes, variables, and approaches each study adopts, hindering a pan-European overview (Camarasa *et al.*, 2019). However, the uneven uptake of EE solutions across countries suggests that the decision context of different types of building owners is important and that findings from one country cannot be unproblematically transferred to another (Heiskanen and Matschoss, 2017).

In this way, further data is needed to deepen the understanding of the following:

- What stakeholders (i.e. actors with a vested interest in the project) play a key role (are the determinant) in the technology selection, taking the whole stakeholder network system into consideration, not only the potential technology adopter.
- What are the main arguments in favour of or against each technology, addressing all relevant EETs
- What EEMs are currently being adopted, distinguishing the various building typologies and project types (e.g. shallow and deep retrofit)

The information should enable cross-country comparison of the results in order to ensure a pan-EU overview of each of these points.

Findings from RQi were used to formulate RQI-III. Thus, these research gaps have been recognised and addressed in the content of this thesis.

# 3. RESEARCH METHODS AND TOOLS

This chapter summarises the methodologies adopted in this doctoral dissertation, highlighting the scientific contribution in each case. It is organised into three sections, based on the specific purpose:

(1) The bibliometric analysis used to characterise the state of research in the field (Paper I);

(2) The survey design developed to gather the primary data (Papers II–IV, common for all);

(3) The methods utilised to assess the retrieved data (Papers II–IV, one method per paper).

## 3.1. Characterising the state of research: A bibliometric analysis

The characterisation of the state of research was performed through a systematic literature review. This means a study with a (i) clear stated purpose, (ii) question, (iii) defined search approach, and (iv) exclusion criteria producing a characterisation of articles. According to (Levy and Ellis, 2006), the main steps in a systematic literature review are as follows: (1) identification of articles through the database, (2) screening, after the filtering and selection of papers, (3) assessing the articles for eligibility and, (4) data analysis and conclusions. Systematic literature reviews are based on a scientific, replicable, and transparent protocol with the aim of minimising human error and bias in the synthesis; and outlining of the analysis (Tranfield, Denyer and Smart, 2003; van Oorschot, Hofman and Halmana, 2018).

To further reduce the bias in the selection and mapping of the article titles, a bibliometric analysis was conducted. Bibliometric analysis is a powerful quantitative tool to explore knowledge networks based on published literature (Tranfield, 2004). It has been widely used for studying the structure and development of various research fields (Martín-Martín *et al.*, 2018), including energy and climate change (Denyer and Smart, 2003). The method involves statistical analysis of published articles and citations to measure their impact (De Bellis, 2009). Bibliometric analysis was found to be the most suitable approach for the analysis in this study as it enables us to perform an entire quantitative assessment of knowledge structures and research trends in the field without having to select or dismiss any title for the selection and mapping or representation, hence reducing potential bias in the analysis process. Co-citation was identified as the most suitable approach for the investigation. Document retrieval was performed following a keyword search term. The retrieved essays deriving from the data collection were then exported in BibTeX format for further filtering and analysis (Visser, 1997). Next, the results were imported to RStudio for the bibliometric analysis (*R: The R Project for Statistical Computing*, 2020). RStudio v.3.51 was utilised as a tool to map and visualise the data and networks from the three established topic areas. Within RStudio, the Bibliometrix package was applied as it is a useful R-tool for comprehensive science mapping analysis. This package also provides various functions for facilitating the understanding and interpretation of network patterns, including analysing the different architectures of a bibliographic collection through conceptual, intellectual, and social structures (Cuccurullo *et al.*, 1948; Aria, M. & Cuccurullo, 2017).

Further details on this methodology (including search terms and exclusions used) can be accessed in Appendix I. “Paper I: Diffusion of energy-efficiency technologies in European residential buildings: A bibliometric analysis”.

### 3.2.Data collection: A multi-country online survey

As identified in the state of research, data on EET adoption in EU residential buildings is presently fragmented or unavailable. To generate this information at a pan-EU scale while addressing all of the variables needed to answer to the RQs, an online survey was identified as the most appropriate research tool. The following section describes the design and operationalisation of the survey as an instrument to collect multi-country consistent data.

In this way, the data used in the analysis was based on data collected from a multi-country survey gathered in 2019. Due to resource availability, only eight out of the EU28 member states were addressed in this thesis: Italy (IT), Spain (ES), Germany (DE), Poland (PL), United Kingdom (UK), France (FR), Belgium (BE), and the Netherlands (NL). The countries were selected based on the following parameters:

- Size and coverage in the EU residential building market: together they represent more than 50% of the whole building stock (Ulterino, 2014). They also cover three of the four bioclimatic zones in the EU according to the Köppen–Geiger climate classification (European Commission, 2016).
- Priority list of countries shared by the funding organization: Climate-Knowledge and Innovation Community (Climate-KIC), supported by the European Institute of Innovation and Technology (EIT).
- Data and local partner availability: the selected countries were readily available to provide the necessary data and support required.

The overall sample contains 7,231 responses. To enable cross-country comparability of the results, all countries used a common survey instrument translated into the local language and jargon.

### 3.2.1. Content and structure of the survey

The questionnaire layout was drafted and reviewed by market experts and pre-tested by stakeholder groups´ representatives (see Table 2) in each of the eight sampled countries. The main purpose of the pre-test was to ensure the comprehensibility of the questions across different contexts and levels of knowledge. It also helped to identify inconsistencies, coding errors, as well as data gaps. The final inquiry was composed of five sections (I–V). The first section was on the characterisation of the stakeholder profile (Section I). Stakeholders were then requested to select their building typology and type of project (Section II). The behavioural factors determining adoption decisions were measured in two ways: first, the respondents were asked to assess the perceived influence, interest, and level of communication with individuals (actors) involved in the selection of the technology (Section III). Following, they were inquired about their level of familiarity with different building technologies. Based on their answer, they were requested to identify the main drivers and barriers in relation to a given technology (Section IV). Finally, questions about contextual factors such as building, and socio-demographic characteristics were posed (Section V). In this study, only results from Sections I and II are included in the analysis.

### 3.2.2. A stratified sample approach

To address all of the variables and stakeholders present in the system, a stratified sample approach was considered as the most appropriate, since (1) the population of interest (i.e. residential building projects in the EU) is significantly large and heterogeneous, and (2), there is a need to represent even the smallest subgroups of the population (e.g. comprehensive retrofit projects,). The sample was then divided into the three main stratification axes as the three main elements or agents defining the universe: (i) stakeholder groups, (ii) building typology and, (iii) project type. In order to ensure the analysis of each stratification axis, a minimum quota was designated per axis (see Appendix VI). The minimum quota per country was established in 500 responses, with a correction factor in those countries with smaller population size (e.g. Belgium).

#### *I. Stakeholder groups*

The list of stakeholders potentially involved in residential building projects (potentially involved in the uptake of EEMs), classified according to their perspective in the project are listed in Table 2. All of which have been included in the sample of the survey.

Table 2. Stakeholder groups and subgroups involved in residential building projects, classified according to their role (Camarasa, 2019).

| # | Stakeholder groups and subgroups | *Main presence in the building value chain* |
|---|---|---|
| **1** | **Conceiving, planning, and consulting services** | ***Planning/design; construction/installation*** |
| | Architect | |
| | Engineer | |
| **2** | **Material and technology suppliers** | ***Technology and material supply*** |
| | Technology or material manufacturer or trader | |

| | | |
|---|---|---|
| **3** | **Construction and installation**<br><br>Construction company<br><br>Installer | ***Construction/installation*** |
| **4** | **Enabling services**<br><br>Local public authorities (e.g. construction permit authorities)<br><br>Bank or other financial services (incl. local branch offices) | ***Overarching and enabling services; economic or business management*** |
| **5** | **Operation and maintenance services**<br><br>Facility manager (incl. commercial, administrative)<br><br>Facility manager (incl. technical, maintenance etc.)<br><br>Energy supply/utility and energy service company (ESCO) | ***Usage and maintenance; economic or business management*** |
| **6** | **Institutional demand side**<br><br>Investor or developer<br><br>Housing company (for-profit)<br><br>Housing company or housing association, cooperative (e.g. public/ part governmental/ non-profit) | ***Real estate; usage and maintenance*** |
| **7** | **Private demand side**<br><br>Private house owner<br>(i.e. private owner but flats rented out)<br><br>Self-occupying private house owner | ***Real estate; usage and maintenance*** |

### *II. Building typology*

The second axis of stratification in the survey was the building typology. Building typology refers to a set of model buildings with their own age of construction, geometrical, thermo-physical, equipment, and energy performance properties (Ballarini *et al.*, 2011). The building composition and energy solutions vary substantially from one building typology to another. Characterising and identifying the building typology is, therefore, critical in the study of energy-efficiency technology measures as it provides essential information about the building composition and energy-efficiency technical measures that can be viably implemented in each case.

As mentioned above, one of the biggest EU initiatives to characterise building typologies across European countries is the IEE TABULA project. In this project, each typology is well-defined by building types with specific parameters. Based on their classification, Table 3 shows the names and definition of the identified building typologies clustered in this study, based on the number of dwellings.

Table 3. Building typologies: acronyms and definitions. Source: Own elaboration.

| Cluster | Acronym | Name |
|---|---|---|
| Single-dwelling building (SDB) | SFH | Single-family house or detached house |
| | SDH | Semi-detached house, twin house, or duplex |
| | RH | Row house or terrace house |
| Multi-dwelling building (MDB) | SMF | Small multi-family home or small apartment building |
| | LMF | Large multi-family home or large apartment building |

### *III. Project type*

The third and last stratification axis of the survey refers to the project types taking place over the course of the building's entire life – from construction to operation, maintenance, modification, and eventual EoL (incl. demolition and waste treatment) (Ran Finnveden *et al.*, 2009). As stated in the scope and limitations section, EoL is out of the scope of this study. In view of this limitation, the project types are classified by the depth and types of interventions, as described in Table 4.

Table 4. Project types: acronyms and definitions. Source: Own elaboration.

| Acronym | Project type | Definition |
|---|---|---|
| **NC** | New construction | Site preparation for, and construction of, entirely new structures and/or significant extensions to existing structures whether or not the site was previously occupied. (United Nations, 1997) |
| **R** | Retrofit (incl. overhaul or potential repair) | Upgrade the function of one or multiple building components. This can also include any necessary action to restore any broken, damaged or failed device, equipment, part or property to an acceptable usable state. (United Nations, 1997) |
| **DR** | Deep retrofit | Extra measures with the aim to upgrade the building to a higher standard. (United Nations, 1997). In the case of this study it refers to the inclusion of energy efficiency measures, such as insulation for the walls, ground floor and attic, air-tightening of the building's envelope, new energy efficient windows, heat recovery, solar cells, etc. |

### 3.2.3. Quota

The minimum quota was defined based on an equally distributed minimum number of responses required in each stratum. This minimum number was defined based on the estimate of some of the sample size calculation approaches outlined by Blair et al., and it has been defined for the three axes of stratification (i.e. stakeholder group, building typology, and project type) (Czaja, Blair and Blair, 2013). One stratification axis is controlled ex-ante (stakeholder group), and two are controlled for during the survey or ex-post (i.e. building typology and project type). The samples were inducted via quota sampling to be representative of the country's population according to the Eurostat NACE classification. The minimum quota established for each stratum can be found in Annex VI [9]. Further information on the survey methodology can be found in (Camarasa, 2019). The complete questionnaire can be accessed through this link[10].

## 3.3.Data analysis: A method per research question

Due to the distinct focus of the RQs, the following section has been divided into three sub-sections, each one addressing a specific RQ and subsequent journal paper.

### 3.3.1. Paper II. Identifying key decision-makers and persuaders in the technology selection: social network analysis

The analysis of the results to answer to RQ I (i.e. Paper II) *"Who are the key decision-makers and persuaders in the technology selection, across building typologies, project types, and EU member states?"* was conducted through SNA.

SNA, sometimes also referred to as 'structural analysis' (Granovetter, 2005), is not a formal theory but rather a broad strategy for investigating and visualising social structures. SNA examines interactions between units in a group through the use of networks and graph theory (Rousseau, 2002). Network structures are characterised in terms of nodes (i.e. individual actors, agents, people, or things within the network) and the links between the nodes (i.e. ties or edges). It has been applied to a multitude of research fields – such as aerospace, anthropology or computer science, etc. – to investigate various relationships among organisations and individuals (Stanley Wasserman, Katherine Faust, 1999; Barrat *et al.*, 2003; Hanneman and Riddle, 2014). In this way, SNA was identified as the most suitable research instrument for the analysis of RQ I as it has demonstrated to be a solid tool to unravel complex interaction patterns within the network, as in the case of building construction projects.

[9] A market size correction was implemented in those countries where the overall population was substantially bigger or smaller the average size (e.g. Belgium or the Netherlands).
[10] https://chalmersuniversity.box.com/v/SurveyQuestionnaire

In this study, the stakeholder groups are represented by nodes (i.e. circles), and their role in the building value chain is represented by a given number. In parallel, the power of the stakeholder in the decision is expressed in the graph through the size of the node. The link between the nodes represents the level of communication between them in technology adoption, where the width of the line represents the level or frequency of their communication. Thus, undirected weighted graphs are traced.

SNA theory broadly distinguishes between two main types of networks, (1) “complete-” or “whole-networks”, and (2) “ego-networks”. In complete network, the relationships between all agents of a social system are analysed. For instance, friendships among students in a classroom, being the students in the classroom the complete population of the study. On the other hand, ego-networks consist of a focal node ("ego") and the nodes to whom ego is directly connected to (these are called "alters") plus the ties among the alters, if any (Rousseau, 2002). Ego-networks rest on an extension of traditional survey instruments and can be combined with random sampling. Therefore, and given that the information to feed the analysis was gathered through an online survey representing a sample of the complete population, ego-networks on roles was selected as the network for the analysis.

In ego-networks, as in many network graphs, the full information about the system is contained in its list of nodes and relations, rather than in the location of the nodes. The location of the nodes is defined by an algorithm and might therefore change according to the plot used to render it (e.g. random configuration, free-hand grouping, circle configuration, etc.) (Freeman, 1978). In this study, the network was created using the Fruchterman-Reingold algorithm – one of the most frequently used methods in SNA– where the sum of the force vectors determines the direction in which a node should move. The step width, which is a constant, determines how far a node moves in a single step. When the energy of the system is minimised, the nodes stop moving and the system reaches its equilibrium state (Github, 2019). In this context, energy is described as the motion or inertia of a force-directed algorithm, such as Fruchterman-Reingold (Github, 2019).

#### *3.3.1.1. Stakeholder groups are involved in the selection of the technology*

The information to identify their role was collected from the first question in the survey: "Are you working professionally in one of the following company or organization types?" Responses from all stakeholder groups were aggregated to ensure a comprehensive understanding of the situation.

In order to identify the main stakeholders involved in the decision, the survey respondents were asked "Who were the most important actors with whom you were in contact for the EE technology selection?" The selected stakeholders were collected in a complete list of nodes, including egos and alteri. Each node was then weighted based on its level of power in the decision.

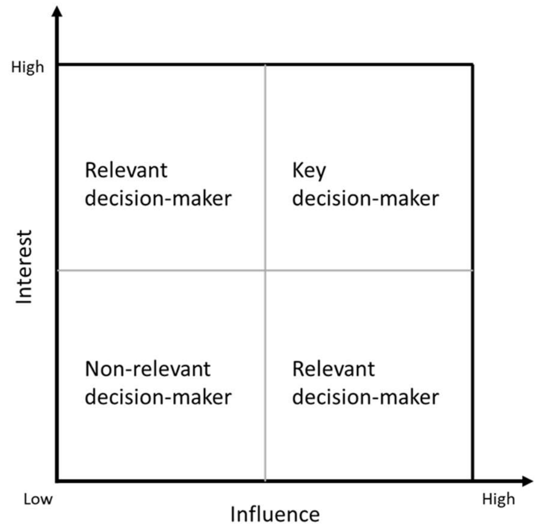
##### *3.3.1.1.1. Definition of key stakeholders*

In this study, stakeholder is defined as an actor or agent with a vested interest in the project. The term "key" refers to a determinant role in the technology selection, which is measured through two main parameters: (1) level of power, and (2) the level of communication with other stakeholders. The method by which these two parameters are measured, are described hereafter.

##### *3.3.1.1.2. Level of power in the decision*

The level of power of each agent in the decision was appraised based on an interpretation of the power-interest matrix developed by Johnson and Scholes (Johnson, Scholes and Whittington, 1983). In this matrix, a stakeholder's power is defined as the ability to influence the project, whereas his or her interest is related to the will to achieve something. Within this study, stakeholders with a high level of interest and influence were considered as key (Figure 3), as it was assumed that a high level of influence and interest enabled them to have a strong capability in the technology selection process. Relevant stakeholders are those who have an impact on the decision but whose opinion might be overruled by key stakeholders.

Figure 3. Parameters identifying key decision-makers. Source: Own elaboration.




Referring to the actors selected from the previous question (i.e. what stakeholders the participants had identified as important in the EE technology selection), the information on the level of power was extracted by the survey questions “What was the level of influence of each actor in the technology selection?” and “What was the level of interest of each actor in the technology selection?”. The answer option was a Likert scale from 0 (*none*) to 5 (*very high*). The weights of the nodes were calculated using a median of the interest for the entire sample plus the median influence for the entire sample, divided by two, as described in (1). This is calculated for each stakeholder group. The calculated level of power per stakeholder group resulted in the complete list of weighted nodes.

$$\textbf{Power}: P(i) = \frac{interest_i + influence_i}{2} \qquad (1)$$

#### *3.3.1.1.3. Level of communication or interaction between each stakeholder in the decision*

According to communication theories, the more often two stakeholders communicate on a particular topic, the higher the chance they will influence each other (Griffin, 2016). In this way, to identify who the key stakeholders in the technology selection were, the frequency of communication was also analysed, herein referred to as “level of communication”. In the survey, the level of communication between the ego and the alter ego was then gathered using the survey question “How often were you in contact with each actor in the technology selection?”, again based on the actors they had selected in the first SNA question. The level of communication among “alteri-alteri” was measured using the question “How often do you assume the actors communicated with each other for the technology selection?” In both questions, respondents were provided with a Likert scale from 0 (*never*) to 5 (*daily*). For all queries, respondents were also given the choice to respond with “I don’t know” and “I had no contact with anyone”.

In a network graph, degree centrality is measured by the total number of direct links with the other nodes, the fundamental formula CD is equation (2). To decrease possible size effects, we normalised the degree centrality using equation (3), where $xij$ denotes the number of links directly connected with node N, and n denotes the total number of the nodes in the focal network.

$$\textbf{Degree}: CD(Ni) = \sum_{j=1}^{n} \boldsymbol{Xij} \quad (\mathrm{i} \neq \mathrm{j}) \qquad (2)$$

$$\textbf{Degree}: C'D(Ni) = \sum_{j=1}^{n} \boldsymbol{Xij} \,/\, (n-1)(n-2), (\mathrm{i} \neq \mathrm{j}) \qquad (3)$$

Due to the use of the Likert scale in the answer option, the level of communication was quantified using the median of the responses. We calculated this level for all respondents, providing *N* ego-networks from which we build the union – specifically, all network relations between roles are combined in one graph. Once the list of weighted nodes and edges was created, we plotted the graph with iGraph and ggnet2 in RStudio libraries (Igraph, 2019).

### 3.3.2. Paper III: A Pearson’s Chi2 and Cramer’s V

The analysis of the results to answer to RQ II (i.e. Paper III) *“What are the drivers and barriers for EETs across the EU member states?”* was conducted through descriptive statistical analysis, using Pearson’s Chi2 and Cramer’s V tests. This type of analysis was deemed the most suitable for our ends as it enabled us to study the drivers and barriers linked to their association across the countries.

To answer to this RQ, the analysis focused on the specific stakeholder groups that the previous paper (Paper II) had identified as key in the technology selection: architects, engineers, construction companies, installers, and demand-side actors. Therefore, a subset of the complete database was used. The final sample used for this study consisted of 1,782 responses, with the following distribution across countries: BE = 115, DE = 181, ES = 317, FR = 209, IT = 329, NL = 216, PL = 204, and the UK = 211. The subset obtained for the above-mentioned stakeholder groups was further divided into two parts: one each for drivers and another one for barriers. In this way, the response to the above questions on drivers and barriers was another dimension defining the sample size. The parts are based on valid responses in the analysis of the driver or barrier groups (i.e. at least one of the choice of answers in the question checked). This division is necessary as the respondents were given the freedom to answer either barrier- or driver-related questions, or both, based on their level of experience and knowledge. The complete list of stakeholders and their respective quotas in the final dataset with valid observations for driver and barrier groups are described in Table 5. The datasets for driver and barrier groups have 1,326 and 1,365 responses respectively.

Table 5. Quota for drivers and barriers per stakeholder groups and countries. Source: Own elaboration.

| | | Quota | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | BE | | DE | | ES | | FR | | IT | | NL | | PL | | UK | | TOTAL | |
| # | Stakeholder groups | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers | Drivers | Barriers |
| 1.1 | Architect | *11* | *13* | 13 | *14* | 29 | *30* | 28 | *27* | 23 | *23* | 19 | *19* | 24 | *22* | 8 | *8* | **155** | **156** |
| 1.2 | Engineer | *16* | *16* | 16 | *19* | 28 | *29* | 16 | *18* | 19 | *18* | 12 | *10* | 34 | *33* | 9 | *10* | **150** | **153** |
| 1.3. | Construction companies | *14* | *16* | 20 | *19* | 26 | *26* | 16 | *15* | 37 | *37* | 28 | *27* | 28 | *26* | 70 | *70* | **239** | **236** |
| 1.4 | Installers | *19* | *19* | 20 | *19* | 26 | *26* | 25 | *23* | 31 | *32* | 22 | *19* | 6 | *5* | 6 | *4* | **155** | **147** |
| 1.5 | Demand-side actors | *31* | *34* | *66* | *75* | *114* | *121* | *67* | *71* | *110* | *127* | *85* | *86* | *88* | *93* | *66* | *66* | **627** | **673** |
| **TOTAL** | | **91** | **98** | **135** | **146** | **223** | **232** | **152** | **154** | **220** | **237** | **166** | **161** | **180** | **179** | **159** | **158** | **1,326** | **1,365** |

The data analysis was then comprised of two parts. The first part estimated the probability of selecting each driver and barrier group for each EET and country combination. As shown in equation (4), the probabilities are the ratio between the numbers of respondents thought a driver/barrier is significant ($r_i$) and the total number of respondents that answered the survey ($N_i$).

$$P_i = \frac{r_i}{N_i} X100\% \qquad (4)$$

In the second part, the level of two-way association between these probabilities and the eight countries was estimated using the Pearson's Chi2 and Cramer's V tests. These statistics measure the two-way dependency between the probabilities of drivers/barriers among the countries. The Pearson's Chi2 was estimated from the number of observations in the matrix ($n_{ij}$) as shown in the equation (5) below, where $i$ is country (rows) and $j$ denotes whether a driver or barrier is selected or not (columns) for an EET and country (Pearson, 1900).

$$Chi2 = \sum_i \sum_j \frac{(n_{ij} - m_{ij})^2}{m_{ij}}; \text{ where } m_{ij} = \frac{(\sum_i n_{ij})(\sum_j n_{ij})}{\sum_i \sum_j n_{ij}} \qquad (5)$$

Since there are eight countries and two options (driver or barrier selected or not), the Chi2 obtained above has a total of seven degrees of freedom i.e., (8-1) * (2-1). The Cramer's V is defined as given in Equation (6) below, where *n* is the sample size and *t* is the minimum of number rows minus the number of columns minus one, giving $t = 1$ in the current paper as the number of rows equal to eight (countries), and the number of columns is equal to two (whether a driver or barrier selected or not). The value of Cramer's V varies between 0 and 1, where 1 describes a high correlation (Cramér, 1946).

$$Cramer's\ V = \sqrt{\frac{Chi2}{nt}} \qquad (6)$$

Pearson's Chi2 and Cramer's V tests evaluate the following hypotheses ($H_0, H_A$):

- *Null hypothesis ($H_0$): There is no change in the influence of a driver or barrier for an EET across the countries.*
- *Alternative hypothesis ($H_A$): There is a change in the influence of a driver or barrier for an EET across the countries.*

The test statistic for Pearson's Chi2 estimated in equation (6) was compared with the Chi2 distribution with degrees of freedom seven and the significance level 5% (i.e. absolute value of probability less than or equal to 0.05). If the test statistic was significant, the $H_0$ could be rejected, demonstrating a significant change in the influence of a driver or barrier across countries.

### 3.3.3. Paper IV: An application of discrete choice conditional logit model (CL)

The analysis of the results to answer to RQ III (i.e. Paper IV) *"What are the EET diffusion gradients across building typologies, project types and EU member states?"* was conducted through descriptive statistical analysis, using a discrete choice conditional logit model (CL). This type of analysis was deemed the most suitable as it enabled us to better capture the user behaviour based on unlabelled alternatives: specifically, each alternative was defined by its attributes. Also, unlike other approaches, such as multinomial logit (MNL) or nested logit model (NLT) models, CL allows estimation of utility as a function of attributes without requiring the user to choose; users can choose any combination of building intervention (BI) including EEMs and non-EE measures, which is observed in the dataset.

Since the analysis focused on building projects, a subset of the complete database was used, excluding any response which did not contain a project type. Subsequently, the final sample used for this study consisted of 4,277 responses, with the following distribution across countries: Spain (n = 511), Italy (n = 722), Poland (n = 545), Germany (n = 526), Netherlands (n = 505), United Kingdom (n = 504), France (n = 501), and Belgium (n = 463).

After retrieving the data, a screening process was performed to remove responses that met any of the following criteria: (1) any of the questions used in the analysis unanswered, (2) completion time of under 8 minutes (which was the minimum tested time to complete the questionnaire), or (3) inconsistent answers (e.g. selecting all of the BIs).

In formulating a statistical model for ordered discrete outcomes, it is common to start with a linear function of covariates that influence specific discrete results (Washington, Karlaftis and Mannering, 2003). Due to the wide number of answer options in the survey question, this was undertaken with the help of a CL based on random utility theory. The objective of the CL is to estimate a function that determines outcome probabilities: in this case, the probability of a certain choice of BIs to occur given a specific choice-set, country, the motivation behind the project, and the combination of project type and building typology, hereafter referred to as "bucket". For each observation in the dataset, nine choices were randomly generated so that not all of the choices were made by a particular observation. In essence, a discrete choice dataset was created, assuming each choice was among 10 choices, where each choice was a combination of BIs. Therefore, the sample size increased 10-fold, giving a total of 25,270 observations. This procedure allowed us to reduce the alternatives in the choice sets to a manageable size, and it is possible because the independently identically distributed extreme value distribution used to derive the CL model allows the use of subsamples (Washington, Karlaftis and Mannering, 2003).

***I. Model Formulations: Main Effects***

These formulations capture the overall effect of BIs, by either country *c*, bucket *b,* or motivation $m$ in selecting an alternative $k$ from a given choice-set (one or combination of various BIs, *i*) using the CL model. The CL model estimates utility as a function of attributes (BIs) and does not consider any particular alternative or a choice-set (set of alternatives). Hence, the CL is capable of estimating the utility for any given choice-set. For example, a choice-set could be a set of 33 BIs, where only one BI could be selected at a time: specifically, 33 alternatives, where each BI is an alternative. The CL model is capable of estimating the probability of selecting each BI (an alternative). Since the CL needs to capture the behaviour with respect to any given choice-set (i.e. a combination of BIs), there is no utility without a BI being an independent variable (binary). Hence, the binary variable for a BI ($X_i$) is present in every utility function of the CL model, as shown below. Simply, without a BI there is no alternative to select from, without an alternative there is no utility of selecting it. Therefore, the presence of $X_i$ in each utility function is explained below. Based on the findings from the data analysis presented in the previous section, it is assumed that the user could choose any combination of 33 BIs for a choice-set and each alternative in the choice-set is independent. The choice-set (*K)* with *n* alternatives is defined in **(7)** below, where each alternative ($k_i$) is a subset of the 33 BIs presented in Table 3.

$$K = \{k_1, k_2, \dots\dots\dots k_n\}, each\ k_i \complement \{X_1, X_2, \dots\dots\dots X_{33}\}, k_i \neq k_j \forall i, j; n\ is\ any\ positive\ integer \qquad \textbf{(7)}$$

The utility of selecting an alternative $k$ from a given choice-set (defined in **(7)**) is defined by ($U_k$) and by an observation $n$ (subscript ignored in the equation for simplicity), with various main effects, shown in **(8)–(11).** These main-effect models estimate the parameters of $U_k$ *(*$\alpha_i$, $\alpha_{ci}$, $\alpha_{bi}$*, and* $\alpha_{mi}$*),* based on the following hypothesis.

*Null hypothesis, H0: The influence of BIs on the selection an alternative k from a given choice-set (defined in* ***(7)****) significantly vary across either by country c, bucket b, or motivation m*

*Alternative hypothesis, H1:H0 is not true.*

**BI model**: Estimates the CL model for the entire dataset, assuming BIs are the only independent variable.

$$U_k = \sum_{i \in EEM}(\alpha_i X_i) + \varepsilon_k \, \forall k \in K \qquad \textbf{(8)}$$

**Country main-effect model**: Estimates the CL model for the entire dataset, assuming BIs and country are the only independent variables.

$$U_k = \sum_{i \in EEM} \delta_c \alpha_{ci} X_i + \varepsilon_k \forall k \in K, c \in Country \qquad \textbf{(9)}$$

**Bucket main-effect model**: Estimates the CL model for the entire dataset, assuming BIs and bucket are the only independent variables.

$$U_k = \sum_{i \in EEM} \delta_b \alpha_{bi} X_i + \varepsilon_k \forall k \in K, b \in Bucket \qquad \textbf{(10)}$$

**Motivation main-effect model**: Estimates the CL model for the entire dataset, assuming BIs and motivation are the only independent variables.

$$U_k = \sum_{i \in EEM} \delta_m \alpha_{mi} X_i + \varepsilon_k \forall k \in K, m \in Motivation \qquad \textbf{(11)}$$

Where,

$k$ = the choice from a given choice-set defined in **(7)**

$X_i$ = is the binary variable for 33 BIs, mentioned in Table 3.

$\delta_c$ = is the binary variable for the eight countries, mentioned in Table 6.

$\delta_b$ = is the binary variable for the five buckets, mentioned in Table 6.

$\delta_m$ = is the binary variable for the five motivations, mentioned in Table 6.

$\alpha_i$, $\alpha_{ci}$, $\alpha_{bi}$, *and* $\alpha_{mi}$ are the model parameters.

### *II. Model Formulations: All Main Effects Combined*

The combined utility of selecting an alternative $k$ from a given choice-set (defined in **(7)**) is defined by ($U_k$) and by an observation $n$ (subscript ignored in the equation for simplicity), in country *c*, and in bucket *b,* and with motivation *m,* is described in **(12)**:

$$U_k = \sum_{i \in EEM} \left( \sum_{c \in Country} \delta_c \beta_{ci} X_i + \sum_{b \in Bucket} \delta_b \beta_{bi} X_i + \sum_{m \in Motivation} \delta_m \beta_{mi} X_i \right) + \varepsilon_k \; \forall k \in K \quad \textbf{(12)}$$

Where,

$\beta_{ci}$, $\beta_{bi}$, $\beta_{mi}$ are the model parameters. A total of 561 (= 33 * (8 + 4 + 5)) parameters are estimated by the logit model.

The model in **(12)** is different from **(8)–(11)** as the former model is capable of capturing the effect of the country, bucket, and motivation simultaneously while the latter models are only capable of analysing one country, bucket, or motivation at a time. The addition of the "$\varepsilon_k$" vector of errors (also called the disturbance term) is supported on a number of grounds, such as the possibility that some potential variables that influence the choice could have been omitted from the equation (Washington, Karlaftis and Mannering, 2003).

The definitions of the binary variables, buckets, motivations, and countries, are described in Table 6. The country and bucket variables are collectively exhaustive: that is, a given observation belongs to one of the eight countries and four buckets. In contrast, motivations are separate binary variables. For example, if an observation include *Environmental* then the variable *Env* = 1. Otherwise, *Env* takes a value of 0, and similarly for the four other motivation variables. As mentioned in Section 3.2, an observation can select multiple motivations.

Table 6. Definition of binary variables (and respective variable names). Source: Own elaboration.

| Country ($\delta_c$) | Bucket ($\delta_b$) | Motivation ($\delta_m$) |
|---|---|---|
| Italy (IT) | Retrofit of single-dwelling building (R_SDB) | Environmental (Env) |
| Spain (ES) | Retrofit of multi-dwelling building (R_MDB) | Technical (Tech) |
| Poland (PL) | Deep retrofit of single-dwelling building (D_SDB) | Economic (Eco) |
| Germany (DE) | Deep retrofit of multi-dwelling building (D_MDB) | Social (Soc) |
| Netherlands (NL) | | Legal (Leg) |
| United Kingdom (UK) | | |
| France (FR) | | |
| Belgium (BE) | | |

### *III. Model Formulations: Probability and Elasticities*

The probability that an observation *n* selecting an alternative *k* in a choice-set in (7) is given by the equation (5), where $U_k$ is defined in equations (8)–(11).

$$P_k = \frac{\exp(U_k)}{\sum_{k \in K} \exp(U_k)} \qquad \textbf{(13)}$$

The elasticities with respect to an attribute ($X_i$) vary with the choice-set. Hence, the elasticities cannot be estimated from the dataset along with the CL model estimation as the dataset does not have a specific choice-set. In this paper, the elasticity with respect to a BI ($X_i$) depends on the number of alternatives in the choice-set ($K$) which contain the BI *($X_i$).* The equations (14) and (15) show the elasticities for (6), where $k'$ *in* $k \in k'$ is the set of all alternatives which contain $X_i$. (Note: since $X_i$ is binary, it could only change from 0 to 1).

$$\frac{\partial(P_k)/P_k}{\partial(X_i)/X_i} = \left(\sum_{c \in Country} \delta_c \beta_{ci} + \sum_{b \in Bucket} \delta_b \beta_{bi} + \sum_{m \in Motivation} \delta_m \beta_{mi}\right) X_i \left(1 - \sum_{k \in k'} \delta_m P_k\right) \ if \ X_i \in k$$

**(14)**

$$\frac{\partial(P_k)/P_k}{\partial(X_i)/X_i} = -\left(\sum_{c \in Country} \delta_c \beta_{ci} + \sum_{b \in Bucket} \delta_b \beta_{bi} + \sum_{m \in Motivation} \delta_m \beta_{mi}\right) X_i \left(\sum_{k \in k'} \delta_m P_k\right) \ if \ X_i \notin k$$

**(15)**

# 4. SUMMARY OF FINDINGS

## 4.1. Key decision-makers and persuaders in the technology selection *(RQ I: How?)*

*RQ I. Who are the key decision-makers and persuaders in the technology selection, across building typologies, project types, and EU member states?*

The results from Paper II (Appendix II) show that, in the stakeholder network the individual level of power and communication vary across the different cases and countries (Camarasa *et al.*, 2020). Nonetheless, in all instances, multiple stakeholders were in communication, thereby potentially influencing each other in the development of the technology selection process. The demand-side actors (i.e. technology adopters) are identified as having the highest power in the decisions, often followed by the engineers, the architects, and the installers. The stakeholder networks show heterogeneity in the stakeholder setup across the sampled countries and also demonstrate that, in the technology selection process, there is not just one stakeholder involved but rather a cohort of actors with distinct levels of power and interaction with each other. Therefore, technology adopters – in most cases the most powerful ones – should not be understood as being the sole decision-makers in the technology selection process. Many other stakeholders are involved and interconnected in these decisions, some of which (e.g. architects, engineers, and installers) can have the same or even more power and communication than the demand-side actors. Therefore, even in the cases in which demand-side actors have the highest influence in the decision, this is in strong communication with other stakeholders who can inform, and therefore affect, their decision.

## 4.2. Drivers and barriers to EETs *(RQ II: Why?)*

*RQ II. What are the drivers and barriers for EETs across the EU member states?*

The findings from Paper III (Appendix III) show that drivers and barriers to EET adoption differ depending on the specific solution and country. Nevertheless, some general conclusions can be drawn. Regarding the potential drivers for the implementation of EETs, key decision-makers and persuaders identified economic and technical aspects as being the most relevant, especially for district heating, heat pumps, photovoltaic, solar thermal, and ventilation (with heat recovery). Concerning the barriers impeding the selection of these technologies, the most frequently selected were economic-related arguments, such as "Lack of trust, awareness of lower life cycle, or running costs". This outcome indicates that the assumed economic viability of these solutions is not sufficiently acknowledged or appealing so as to foster their large-scale deployment in the selected countries. This coincides with some of the findings from previous studies (Popesc*u et al*., 2012), which try to monetise other impacts of the BIs in order to make these actions more appealing to the decision-makers (Popescu *et al.*, 2012; Ürge-Vorsatz *et al.*, 2015).

### 4.3. Cross-EU diffusion gradients of EEMs *(RQ III: What?)*

*RQ III. With what gradients are the technologies spreading across the EU member states?*

The results of Paper IV (Appendix IV) expose the BIs identified as the ten highest-ranked as being most of them related to the building envelope, namely: maintenance of the wall, maintenance of the envelope plus new energy generation, upgrade of the wall, maintenance of the roof, maintenance of the envelope plus upgrade of the energy generation, new element energy generation, new energy storage, upgrade of the roof, upgrade of the envelope plus new energy generation, and new ventilation. These BIs related to the building envelope are also complemented with other actions related to energy generation (i.e. new energy generation). As expected, these BIs address a single building element or technology, rather than a cohort of these solutions. When looking at each of the choices, the intervention maintenance of the wall is highly selected across all the countries. The maintenance of the roof is high for all countries except ES. The upgrade of the windows as a single intervention is high for all countries except for IT and DE. The upgrade of the roof is high for all of countries except DE and the UK. Regarding including a new ventilation system, FR and BE show the lowest values. However, and common to almost all instances, current BIs are not sufficient to achieve nZEB standards.

# 5. DISCUSSIONS AND CONCLUSIONS

## 5.1. Key contributions

This thesis advances an understanding of EET diffusion in EU residential buildings by systematically addressing the underlying answers to (1) who is behind the technology selection, (2) what are their perceived drivers and barriers in relation to each of the EETs, and (3) what EEMs are being implemented across various countries, building typologies, and project types.

The key contributions of this thesis are the following:

i. Quantitative bibliometric analysis to characterise the state of the art in the field
ii. A novel scientific methodology to include a bundle of quantitative research methods developed from qualitative constructs characterising renovation decisions
iii. Results of a multi-country representative survey measuring decision variables across multiple stakeholder groups and EU member states
iv. SNA to map and identify key decision-makers in the selection of a technology
v. Quantitative assessment of drivers and barriers to selected EETs
vi. Discrete choice CL model to identify the probabilities of certain EEMs taking place across distinct building typologies, project types, and EU member states

As such, this thesis is an original attempt to link contextualised qualitative research on EE practices in EU dwellings with more narrowly framed quantitative modelling of EET adoption decisions. This is a critical area for researchers to develop further as it draws on empirical characterisations of decision-making to build a rigorous, replicable, and evidence-based understanding.

## 5.2. Results compared to previous research

### 5.2.1. Key decision-makers and persuaders in the technology selection *(RQ I: How?)*

The results of Paper II (RQ I: How?) corroborate judgements from other studies pointing at demand-side actors as key decision-makers in the selection of technology (Nair, Gustavsson and Mahapatra, 2010; Hecher *et al.*, 2017). However, findings also identify other key stakeholders in the decision process, such as installers and engineers in particular. Additionally, the study also provides a systematic understanding and visualization across building typologies and project types, which is to the best of knowledge, the first time this has been done.

### *5.2.2.* Drivers and barriers to EETs *(RQ II: Why?)*

The findings from Paper III (RQ II: Why?) verify those from other studies inasmuch they identify economic-related arguments as key barriers and drivers in the adoption of EETs (Jaffe and Stavins, 1994; Appolloni *et al.*, 2014). Nevertheless, they also uplift some other drivers and barriers that had not been so strongly pointed out in the literature (e.g. social ones) (Michelsen and Madlener, 2013). Another novelty of the results in relation to the previous literature is the overview of the variability across the various technologies and geographies. This provides an understanding that had not been presented before in such a consistent manner.

### 5.2.3. Cross-EU diffusion gradients of EEMs (RQ III: What?)

The conclusions from Paper IV (RQ III: What?) verify those from other studies, such as the fact that most EEMs occur in individual measures instead of being cohesive with a wider set of actions (Walter and Martin, 2005). It is also noteworthy that two of the 10 most frequently implemented actions are single-element preservation actions (i.e. maintenance of the wall and maintenance of the roof), which not necessarily guarantee the deep energetic upgrade that is needed in the EU BS to achieve carbon mitigation targets. A novel insight is that environment-related motivations such as environmental awareness play a key role in the implementation of such measures in some countries (e.g. ES and PL). However, as much as the motivation behind the project might be related to environmental concerns, techno-economic barriers, such as high initial costs, still hinder the adoption of many of the specific EETs in most of the sampled countries.

## 5.3. Contribution to technology diffusion theories

The findings from Paper II contribute to the interpretation of Everett Rogers' theoretical framework in the EU residential sector. In his model "Five Stages in the Innovation-Decision Process", where he assumes that the "Decision-Making Unit" is only applied to the potential technology adopter (Rogers, 1983). However, with the results from this paper, we demonstrate that, in the EU residential sector, non-adopters are still part of the institutional context in which those decisions are framed. Furthermore, some of these non-adopters are also key contributors to the knowledge and persuasion phase leading to the final decision (i.e. adoption or rejection of the technology). This expands the scope of the "Five Stages in the Innovation-Decision Process" model to address not only the potential adopter of the technology but also any stakeholder that the adopter is in communication and that has the capacity or power to affect or determine their final choice (i.e. key persuader).

Some prior studies, such as those using ABM, portrayed various stakeholder groups in the selection of EETs. Nevertheless, to the best of our knowledge, it is the first time that the level of power and communication of each of the stakeholder groups across building typologies and project types in the context of residential buildings in the EU has been systematically proven. Thus, our results confirm the role of key decision-makers and persuaders in the selection of technology.

## 5.4. Evaluation of research

### 5.4.1. Scope limitations

This thesis focuses on the building level and therefore does not address the complete energy-efficiency value chain, such as distribution networks or other energy generation sources. This limitation should be contemplated when contextualising the results. In order to ensure the optimisation of the EE transformation, the outcome from this thesis should be complemented with an understanding of the input of the primary energy of the collective system, as indicated by the results of the Heat Roadmap Europe project (Paardekooper, Lund, Mathiesen, Chang, *et al.*, 2018; Paardekooper, Lund, Mathiesen, Ojeda, *et al.*, 2018).

Additionally, and due to time constrains, the content of this thesis was restricted to technology diffusion theories. Further efforts would be required to broaden this understanding connecting it to other disciplinary approaches, such as behavioural economics (i.e. paying attention to the framing and reference points for decisions and influence heuristics in the EET adoption), or sociology (i.e. analysing social, cultural and technical determinants of energy demand embedded in routine behaviour) (Wilson and Dowlatabadi, 2007; Paroutis and Heracleous, 2013).

### 5.4.2. Approach limitations

One of the greatest limitations of the approach presented in this thesis is related to the broad scope of the study. This has impacted the research project on different levels and phases, particularly during the data collection. First, the fact that the survey had to be distributed in multiple countries, each one of them with a distinct culture, language, and know-how derived in a considerable challenge during the design and pre-testing phase of the survey. It also required considerable resources in its distribution phase. In fact, further EU countries was restricted due to time and capital limitations. Second, additional efforts were needed to ensure that the content was understood and answered correctly across the multiple contexts, stakeholder profiles and respective levels of understanding. To ensure this some questions had to be streamlined or removed and some technical terms adapted or translated. Third, the ambition of encompassing all of the selected variables (i.e. countries, building typologies, project types, and stakeholder groups) while ensuring the minimum quota in a single survey demanded a substantial time investment in the architecture design and coding of the questionnaire. The challenge was to ensure that all of the variables were addressed in the minimum time possible while not being too dense or complicated for each of the stakeholder profiles, as this would have resulted in a high dropout rate and potential rise to sampling bias (Aday 1996; Babbie 1990; Backstrom and Hursh 1963; Rea and Parker 1997).

The stratified sample approach of the survey also involved a number of shortcomings. The first one is related to the fact that it required a minimum number of responses per stratum. Given the high number of strata defined in this study, to effectively characterise the building market, a high number of responses were required per country. Also, some stakeholders and building typologies were more challenging to address than others (e.g. installers, deep retrofit). Another limitation due to the stratified sampling is related to the data analysis, as the data may not reflect the population. This issue, in the context of this thesis, was overcome through disaggregate modelling by incorporating the characteristics of the stratum (Paper IV). In particular, the CL model estimates probabilities at each axis (i.e. bucket, country, and motivation) levels to eradicate the aggregation errors caused by estimating overall means or shares. The paper deals with each stratum individually to address the aggregation errors. However, it does not pledge erroneous estimates from the sample.

## 5.5. Implications of results

This thesis has several implications both for science and practice in terms of its findings and methodological contributions.

### 5.5.1. Scientific implications

On scientific ground, the work presented in thesis can be used as a structure to characterise the adoption of EETs in the EU residential building stock enabling cross-country comparison of the results. In particular, the results from Paper I provide an illustration of the data gaps and research needs in the field. This information can be of use to the scientific community as indications for future research streams and topics. The methodology for stakeholder mapping in the technology selection for EU residential buildings, as presented in Paper II, advances in the application of tools and graph theory to visualize the complete stakeholder network. Furthermore, the outcome of Papers II offers an overview of key decision-makers and persuaders in the technology selection. This information can be of use for future studies as a guidance on the stakeholder groups, which should be included when studying technology diffusion, beyond the potential adopters (i.e. demand-side actors). For its part, Paper III complements this insight by offering an understanding of what are main drivers and barriers for each of these stakeholder groups. The model developed in Paper IV can be useful to other piers as a structure that allows the characterization of BI allowing the stratification building typologies, project types and geographies.

### 5.5.2. Practical implications

Beyond a scientific audience, the results of this thesis have some practical implications that are worth enumerating. In overall, as mentioned above, a primary application of this study is as evidence for the development of national and cross-national policy instruments to foster the large-scale diffusion of EETs. Policy instruments can be classified into push- (e.g. regulatory and control instruments), and pull mechanisms, (e.g. economic or fiscal incentives, education programs, and support tools for voluntary action). Findings from Papers II and III can be particularly interesting for pull mechanisms. The results can be used, for instance, as market evidence by the design of educational programs to support the identification of key stakeholder groups (i.e. decision-makers and persuaders) to design the tailored content based on their level of understanding and perceptions (i.e. drivers and barriers). Paper IV, on the other hand, can be particularly useful for push instruments. Results from this study show that, in most instances, the measures implemented are not sufficient to achieve nZEB standards, subscribing the results from (Groezinger *et al.*, 2014). It also shares insights of what EEMs versus the overall BIs that are currently taking place. These findings could serve as evidence to develop building codes and standards on a national and pan-European level to enforce selected EEMs and actions across the building typologies and geographies. Furthermore, it can be used in public management to support managerial activities in public organizations related to the building sector by providing insights into what EEMs are currently taking place versus the ones that should be promoted.

Likewise, the results from this thesis can be used to support for technology-supply marketing campaigns to foster the adoption of these technologies in the market, by identify stakeholders to target their marketing campaigns (Paper II), adjust the message for each stakeholder group based on their perceptions (Paper III), and align on what EETs within their portfolio should be promoted in what building typologies (Paper IV).

It should be noted, however, that the current results might not necessarily have the right format to directly feed into these two functions. Further efforts are needed to translate the present form of the results to a more useful one for the user of this information.

# 6. OUTLOOK

The work conferred in this thesis introduces several aspects to the field of EET diffusion that establish the basis for future work and can therefore be expanded into different research directions.

From an energy perspective (Mathiesen *et al.*, 2019), a potential development of this work could be to consider the whole energy system. This is, extend the system boundary from the building-scale to the complete energy system network, including primary energy, as well as its transmission and distribution. This extension could be crucial, for instance, when assessing the EE of district or city energy supply. Likewise, further building types and uses, such as non-residential and mixed-use buildings could be addressed.

In addition to this, the methodological framework developed in this thesis could be systematically spread to the remaining EU member states to ensure a pan-EU overview.

Likewise, further research could be undertaken to include other theoretical frameworks or theories, in (e.g. behavioural economics and sociology) or outside decision-making in the context of residential energy use (e.g. practice theory, institutional theory, etc.).

An inevitable step and development of this research is to continue to analyse the dataset. For instance, through deepening the understanding of the intricacies among the various commissioners of the building projects, such as: investors or developers, housing companies (for-profit), housing company or housing association, cooperative (public/ part governmental/ non-profit), private house owner (private owner with flats rented out or self-occupying private house owner). In this way, future investigations can develop and complement the current results by delving into the differences and commonalities among the various stakeholder groups and sub-groups in relation to their levels of power, communication, as well as perceived drivers and barriers to the selected EETs (Papers II-III). Furthermore, part of the data collected through the online survey remains untapped. This information should be analysed and linked to the current study, such as the heating system questions exploring into: what was the energy carrier of the heating system that has been maintained or repaired, what was the heating system before the upgrade, what was it upgrade to, and was the system before the replacement. These insights could serve as a basis to complement the understanding of EEMs currently taking place in the selected countries.

Once this information has been collected, the empirical evidence in the diffusion of EETs, as presented in Papers II–IV, can be advanced to create a comprehensive ABM to better assess future demand of EEMs across EU countries, residential building typologies, and project types. Such a model could take into consideration all stakeholders involved in the decision (Paper II) and their drivers and barriers in relation to specific technologies (Paper III), validated by the probability of a certain EEMs taking place in each case (Paper IV). This information, in turn, could be used to support the evaluation of economic policy measures and policy recommendations (Christof Knoeri, Igor Nikolic, 2014). Furthermore, given that most BSMs only address economic factors in the technology selection process (e.g. investment maintenance or energy costs), the inclusion of such an ABM into BSM could ensure a more accurate assessment of technology diffusion patterns in these models through a comprehensive representation of the decision-making process in technology adoption.

Over time and with further learning, BS is likely to continue to improve, aided by open access to more information and the development of new data-generation techniques, such as CityGML energy ADE (Nägeli, 2019). Within this development, this research can play an important role in providing a framework to better assess technology diffusion dynamics and enhance the appraisal of the BS market dynamics.

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# 8. APPENDICES

This doctoral thesis comprises the following appendices:

| No. | Title |
|---|---|
| **I** | Paper I: Diffusion of energy-efficiency technologies in European residential buildings: A bibliometric analysis |
| **II** | Paper II: Key Decision-Makers and Persuaders in the Selection of Energy-Efficient Technologies in EU Residential Buildings |
| **III** | Paper III: Drivers and Barriers to energy-efficient technologies in residential buildings in the EU |
| **IV** | Paper IV: Cross-EU diffusion of energy-efficient measures in residential buildings. An application of discrete choice modelling |
| **V** | Building technologies and components |
| **VI** | Survey minimum quota |