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Modelling decisions on energy-efficient renovations: A review

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ABSTRACT

The buildings sector accounts for more than 30% of global greenhouse gas emissions. Despite the well-known economic viability of many energy-efficient renovation measures which offer great potential for reducing greenhouse gas emissions and meeting climate protection targets, there is a relatively low level of implementation. We performed a citation network analysis in order to identify papers at the research front and intellectual base on energy-efficient renovation in four areas: technical options, understanding decisions, incentive instruments, and models and simulation. The literature was reviewed in order to understand what is needed to sufficiently increase the number of domestic energy-efficient renovations and to identify potential research gaps. Our findings show that the literature on energy-efficient renovation gained considerable momentum in the last decade, but lacks a deep understanding of the uncertainties surrounding economic aspects and non-economic factors driving renovation decisions of homeowners. The analysis indicates that the (socio-economic) energy saving potential and profitability of energy-efficient renovation measures is lower than generally expected. It is suggested that this can be accounted for by the failure to understand and consider the underpinning influences of energy-consuming behaviour in calculations. Homeowners' decisions to renovate are shaped by an alliance of economic and non-economic goals. Therefore, existing incentives, typically targeting the economic viability of measures, have brought little success. A deeper understanding of the decisions of homeowners is needed and we suggest that a simulation model which maps the decision-making processes of homeowners may result in refining existing instruments or developing new innovative mechanisms to tackle the situation.

Keywords: Energy efficiency; Renovation decision; Modeling; Incentive instruments; Bibliometrics; Citations

Contents

1 Motivation

The buildings sector is responsible for over one third of global greenhouse gas (GHG) emissions [1]. Therefore, a critical focus on the building sector may be crucial for acting on climate change [2]. It is generally accepted that renewable energies and energy efficiency are important opportunities for mitigating GHG emissions [3,3–5]. Renewable energy technologies replace fossil fuel-based technologies for energy production while energy efficiency measures reduce the energy used to provide the same level of energy service. The energy-efficient renovation (EER) of buildings may address both renewable energies (e.g. installation of a heating system based on renewable energies) and energy efficiency (e.g. improvement of the building shell). Environmental benefits resulting from EERs must be seen against their environmental impacts such as the production of insulation materials, their transportation, assembling and disposal at the end of their lifecycle. Asdrubali et al. (2013) state that such a comprehensive view is of particular importance with respect to Nearly Zero Energy Buildings, „for which there is a real risk of shifting the impacts from the operating phase to the construction and end of life phases risk of shifting the impacts from the operating phase to the construction and end of life phases" [6]. Xinga et al. (2011) reviews technologies applied to reach zero carbon in existing buildings [7]. EERs are economically viable in many cases and have great potential to reduce GHG emissions.

Several authors point out that there are profitable ways of reducing emissions in buildings [8–11]. Nauclér and Enkvist (2009) compared abatement costs, capital intensity and the abatement potential of different sectors worldwide projected until 2030 (see Fig. 1). The comparison shows that abatement measures in the building sector provide a comparatively high potential for reducing GHG emissions and at the same time have a large positive net profit (negative abatement costs) for the client. Nauclér and Enkvist (2009) state that upfront financing might be challenging because measures are relatively capital intensive [9].

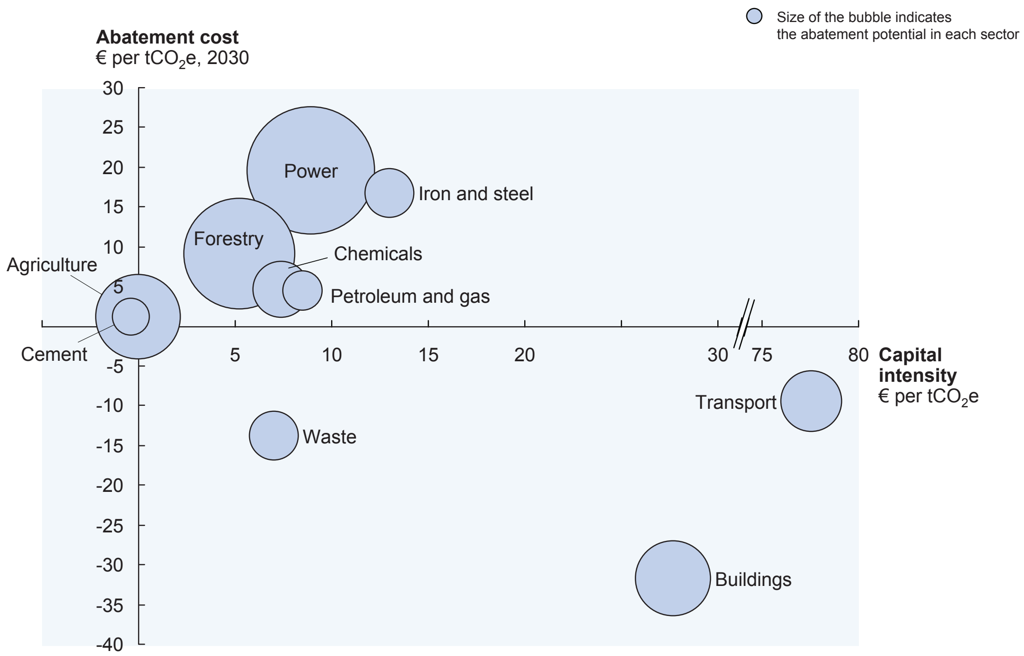


Fig. 1 Capital intensity and abatement cost across different sectors [9]

A high potential for decreasing energy consumption at negative net cost by installing energy-efficient building elements is also acknowledged in the residential building stock of European Union (EU) Member States [12]. Of the total final energy consumption at EU level in 2010, buildings represent about 40% [13,14] of which 67 is for end-use space heating [15]. Therefore EER measures to reduce GHG emissions are very important. This is encouraged by several climate protection scenarios at national, international and global level, which suggest an increase in EER adoption rates and evidence of more large-scale refurbishment of buildings [16–18]. Baek et al. (2012) states that "existing residential buildings are expected to play an important role in enabling countries to achieve their goals of reducing greenhouse gas emissions" [19]. This was also recognised by the EU, which introduced a Directive on Energy Performance of Buildings in 2002 (recast in 2010). The directive requires member states to introduce policies on building energy efficiency [20].

In spite of recent encouraging trends, it is difficult to understand why there appears to be a reluctance to take advantage of these opportunities. In order to tackle this challenge one needs to identify and understand its root cause. A preliminary review of the scientific literature and several project reports was carried out to obtain an initial insight and understanding about the current state of research. Our findings from this review and expert discussions led us to formulate three hypotheses:

- Hypothesis I – Technical options and economic viability
  Technical options to decrease energy demand by EER measures are well understood [21] and, in many cases, economically viable [9,22].
- Hypothesis II – Decision-making processes and incentive instruments
  Several incentive instruments are available to motivate homeowners to thermally upgrade their houses. The decision-making processes of homeowners are not sufficiently understood; Policy makers can only surmise

the effect of instruments before implementing them, which leads to unsatisfactory results [23]. Reviews of existing instruments are then conducted [24], consuming a considerable amount of time and resources.

- Hypothesis III – Models and simulation
  Despite the fact that models are available that explore the decisions of homeowners regarding EERs [25–27], relevant factors and mechanisms to simulate the entire decision-making process are ignored.

A comprehensive review of scientific papers is conducted to evaluate these hypotheses. The following questions are posed to facilitate the analysis:

- What are the most important papers?
- What are the most important references used?
- What are their findings concerning our hypotheses?

In the following sections we elaborate on the methods used to map the research on EERs and identify the most important papers concerning our hypotheses. Results of the paper network analysis and a review of the most important papers is presented in section four. The paper closes with conclusions and recommendations.

2 Approaches to citation network analysis

The review was carried out using bibliometrics, which aims “to shed light on the process of written communication and of the nature and course of development of a discipline” [28]. We performed bibliographical analyses to explore the following core areas on EER relevant to our hypotheses: technical options, understanding decisions, incentive instruments, and models and simulation. Hypothesis II was examined by applying the analyses to two paper sets, one on: understanding the decision-making processes of homeowners and one on assessing the effectiveness of existing incentive instruments. The importance of papers within our core areas is operationalised by a citation network analysis.

There are different approaches for analysing the network of citations in a group of papers. The most important representations are a direct citation network, with co-citation coupling, an analysis of co-citations, and bibliographic coupling of the referencing documents [29]. They all create a network, linking documents, but what represents edges and nodes differ between the approaches. See figure 2 for an overview.

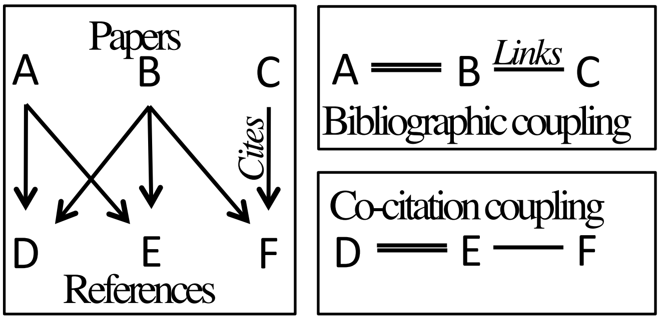


Fig. 2 Schematic overview of different approaches to citation network analysis; adapted from Boyack and Klavans 2010 [30]

A **direct citation network** shows the direct references between documents (A links to D and E, similar to the left picture in Fig 2.).

Co-citation coupling develops a cluster of cited documents, also called the “intellectual base” in bibliometrics [31]. A relationship between two references is established if both are cited by another paper (i.e. a link between D and E, because both are cited by paper A in Fig. 2).

Small (1973) states that frequently co-cited papers, which are necessarily frequently cited individually as well, represent the key concepts, methods or experiments in a field. The patterns can than be used to map out in great detail the relationship between those key ideas [29]. Osareh (1996) concludes that “in a specific field and period of time the most cited papers are the most useful or important papers, and also the most co-cited papers are the most related papers” [32]. Cawkell and Newton (1967) point out that by using co-citation as a part of the automatic clustering procedure, it is assumed that frequently cited papers are more important than less cited papers and that frequently co-cited papers are significant and related in subject to each other [33]. A co-citation analysis is a variant of co-citation coupling, in which the shared references are also linked to the referencing document (D and E are both linked to A, next to the link between D and E).

Bibliographic coupling links two papers if they cite the same document and results in clusters of citing papers [34] (i.e. a link between A and B, because both cite D in Fig. 2). In bibliometric terminology, a cluster of citing papers creates a research front, i.e. using similar parts of the intellectual base [31]. Papers that share references are an indication that a probability exists (with unknown value) that they contain a related subject matter [35]. Jarneving (2007) confirms that bibliographic coupling can be used to link papers that have a similar research focus [36].

A study by Boyack and Klavans (2010) that compares the accuracies of different cluster solutions concludes that a direct citation network is by far the least accurate approach to map the research front. Bibliographic coupling “gave the most accurate solution, followed closely by co-citation analysis” [30].

In our research we used bibliographic coupling and co-citation coupling to obtain a detailed view of the research front and intellectual base, and additionally performed a co-citation analysis. Data collection for the implementation of bibliographic coupling and co-citation coupling and analysis is described in the following section.

3 Data collection

A keyword-based search was performed in the *Scopus* scientific database [37]. Falagas et al. (2008) state that *Scopus* covers a wider range of journals than other databases such as *PubMed* and *Web of Science* [38]. Chappin and Ligtvoet (2014) note that it purportedly also encompasses more modern sources than further databases such as *Web of Knowledge* and *Google Scholar [39]*. A preliminary literature search on *energy efficiency, save energy, decrease energy consumption* and *renovation, retrofit* and *refurbishment* resulted in a set of nearly 3,000 papers. By looking through the titles we found large numbers of papers undoubtedly not addressing our research area. Examples are retrofitting heat exchanger networks, applications of self-heat recuperation technology to crude oil distillation and a study of the interrelation between mean radiant temperature and room geometry. We chose to revise the search terms in order to acquire a more appropriate paper set. From the initial set, the keywords specified in the papers were listed and ranked. We used these keywords to increase the number of relevant papers and decreasing the number of irrelevant papers in the findings. In an iterative process we tried various combinations of highly ranked keywords to improve the focus of the search. With this approach we obtained a reasonable number (689) of papers addressing our research area. We found that it was crucial to add terms specifying the renovation *object* to remove irrelevant papers. The following terms were used to obtain the final result: *Energy efficiency*, accompanied by *save energy,* as well as, *residential/commercial building, home, house* or *dwelling,* together with *retrofit, renovation* and *refurbishment* [1]*.* We recorded bibliographic data (authors, title, year, abstract, keywords, references) across 689 papers.

Within this set we looked for those papers that specifically address our four core areas (listed again below). We applied a similar iterative process, making use of the keywords from the papers to find appropriate search terms:

- Technical options: *heat/thermal insulation, heating system*
- Understanding decisions: *motivation, barrier, decision process/making*
- Incentive instruments: *subsidy, regulation, incentive, energy tax, financial support*
- Models and simulation: *model, simulation*

[1] The search query used is: ((energy W/5 efficiency) OR (save energy)) AND ((residential W/5 building) OR (commercial W/5 building) OR dwelling OR home OR house) AND (retrofit OR renovation OR refurbishment). W/5 limits to search results that are less or equal than 5 words apart.

An overview of the most popular keywords for each of the subsets is provided in Table 1; it is shown that energy efficiency, energy utilization, buildings, energy conservation and retrofitting are popular across all sets. We realise that some intuitive keywords may not be present. One reasoning is that they do not make the four core areas distinct. An example of this latter are keywords regarding economic aspects. They are not used as search terms, but are present in the findings: keywords such as 'costs' or 'investments' are well established in the top keywords for all paper sets (see Table 1).

Because references were not provided for all papers, not all papers could be analysed (449 out of 689 papers were analysed). However, by including an analysis with co-citation coupling, which includes the references in the papers that could be analysed, the set of papers increased to almost 7,000. As a consequence, we are confident that the most important research is covered by our analysis.

Table 1 Popular keyword and number of analysed papers within the paper sets. Papers for which references could not be retrieved are omitted from the analysis. The first keyword related to economic aspects is included.

	Full paper set	**Technical options**	**Understanding decisions**	**Incentive Instruments**	**Models and simulation**
Popular keywords (number of different keywords)	1. energy efficiency 2. energy conservation 3. retrofitting 4. energy utilization 5. buildings ... 16. investments (4,277)	1. energy efficiency 2. heating 3. energy utilization 4. retrofitting 5. buildings ... 17. costs (1,305)	1. energy efficiency 2. retrofitting 3. buildings 4. energy utilization 5. decision making ... 7. investments (649)	1. energy efficiency 2. retrofitting 3. energy utilization 4. energy policy 5. carbon dioxide ... 9. investments (963)	1. energy efficiency 2. energy conservation 3. energy utilization 4. buildings 5. retrofitting ... 15. costs (1,807)
Analysed (% of total)	449 (65%)	98 (70%)	53 (93%)	85 (83%)	152 (76%)

The data (see Appendix A.1) was processed by using the work of Chappin and Ligtvoet (2014) [39]. We adapted that work to link paper designations (Pattern of Author, Title, Year, Source title, Volume, Issue) and references based on the various approaches to citation network analysis (see Appendix A.2). *Gephi* [40] was used to visualise and explore the paper networks.

4 Analysis of paper networks and key papers

In order to focus on our core areas, we analysed four subsets within our full set of 449 papers. These subsets are different in size and partially overlap, as shown in Fig. 3. The largest overlap occurs between the subsets of papers on 'Technical options' and 'Models and simulation' (41).

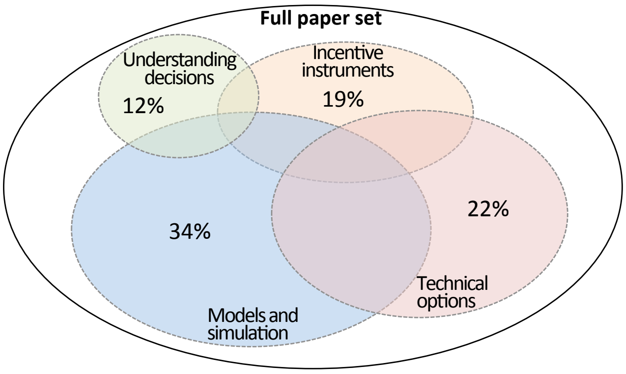


Fig. 3 Schematic overview of subset shares within the full paper set

We identified several key papers and references by examining the bibliometric networks of the four subsets, using bibliographic coupling and co-citation coupling (see Appendix B.1). Our core areas includes 60% of the papers in the full paper set. The other papers were checked for relevant papers. Two papers [41,42] were identified and added to the key paper analysis in the core area 'Understanding decisions'. The other paper do not explicitly concern our core areas, apart from peripheral issues, such as sound insulation of buildings, resource management in smart homes or indoor lighting facilities.

The purpose of the following sections is to present the outcome of bibliographic coupling (research front) and co-citation coupling (intellectual base) in detail and to interpret the results in order to evaluate our hypotheses. We start with presenting central research areas identified by a network analysis of the full paper set. Subsequently we give an overview of findings arising from the paper network analyses of the different subsets and explicitly work on our hypotheses. To this end, we focused on key papers, which are assumed to reflect the research front and intellectual base within our core areas. Since no further key papers were found through our co-citation analysis we abstained from presenting its outcomes.

4.1 Central research areas

The bibliometric networks were visualized and clustered[2]. Clusters were labelled by working through titles and abstracts of clustered papers. Fig. 4 illustrates the paper network of the full paper set resulting from bibliographic coupling (triggered by the number of shared references). It can be seen that Clusters 1-4 are strongly interconnected and they represent the four core areas, technical options, models and simulation, incentive instruments and understanding decisions. Clusters 5 through 8 are more separate and do not explicitly focus on our four areas.

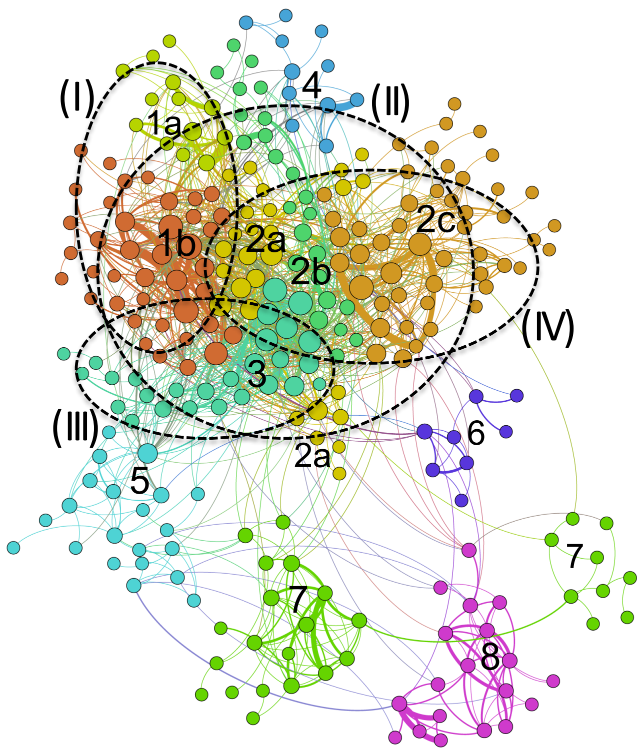
Within the densily connected clusters we found two central topics – economic assessment and behaviour (Clusters 1 and 2). One cluster focusing mainly on policies (Cluster 3) is strongly interconnected to the previous ones. This is not

[2] We used Gephi, an interactive visualisation and exploration platform for all kinds of networks. The data was imported (see Appendix A.2) and displayed according to the Yihan Hu Layout. Clusters are identified by using a heuristic method based on modularity optimisation [43].

surprising as policies tend to influence behaviour by using incentive instruments. A smaller cluster (Cluster 4), tied to the others, refers to maximising energy savings by retrofits and optimising strategies for specific cases.

Most papers within Cluster 5 are case studies on the refurbishment of buildings in north China. Addressing economic issues keeps the cluster in the vicinity of the more interconnected clusters (1-4). Another cluster of papers on China (Cluster 6) addresses performance evaluations of refurbished buildings. Clusters on new approaches and statistical models (Clusters 7 and 8) are rather disconnected from the others. Their broad focus and methodology is quite detached, leading to the predominant use of a different intellectual base.

Surprisingly, we found three clusters referring to China and one to Ireland although neither of these countries were included as keywords in our keyword-based search. While subject areas of the subsets ‘Models and simulation’ (economic assessment, optimization, statistical models), ‘Understanding decisions’ (behaviour analyses, understanding behaviour, non-economic benefits) and ‘Incentive instruments’ (policies) emerge, no cluster particularly focuses on ‘Technical options’. Furthermore, we did not expect the formation of a cluster on new approaches and statistical models (Clusters 7 and 8). These were not addressed by our hypotheses, but seem to be important subject areas in our field as well. Because their methodology is quite distinct, they quote other sources and are therefore placed relatively far apart from the others.



Cluster	Topics
1a	Economic assessment, Ireland
1b	Economic assessment, China
2a	Behaviour analyses
2b	Understanding behaviour
2c	Non-economic benefits
3	Policies
4	Optimisation
5	Case studies, China
6	Performance evaluations, China
7	New approaches
8	Statistical models

Fig. 4 Paper network of the full paper set resulting from bibliographic coupling. Nodes represent papers and links represent shared references between papers. Larger nodes have more shared references. Approximate location of subsets are indicated with: (I) Technical options, (II) Models and simulation, (III) Incentive Instruments and (IV) Understanding decisions. Colors indicate the listed clustered topics (1-8).

The network analysis of the full paper set gives an overview of the main topics within our research area. We analysed the paper networks of the different subsets in order to obtain a deeper understanding of the research structure and central discussion topics. Main clusters were labelled for that purpose. Subsequently we reviewed the identified key papers.

4.2 Technical options

The research front on 'Technical options' contains clusters on North China and the United Kingdom (see Fig. 5). No relation was noticed amongst the papers in the other clusters.

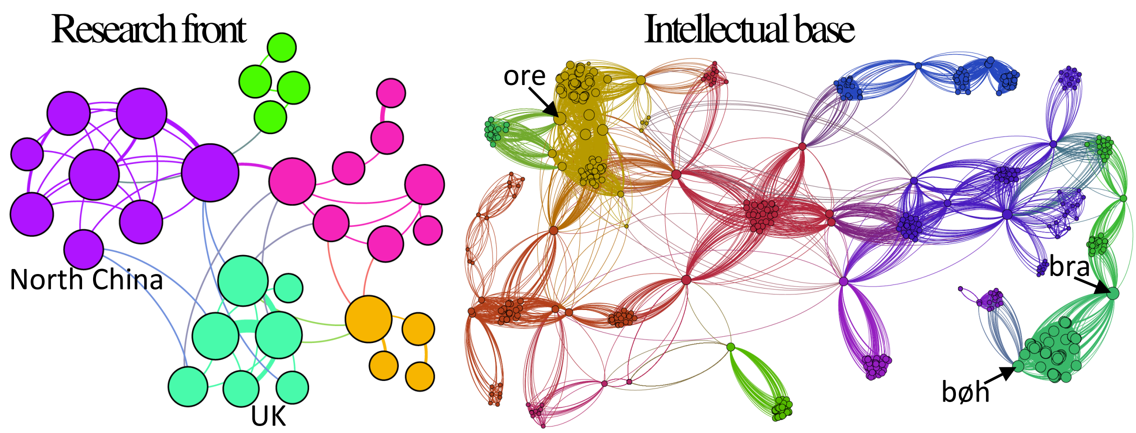


Fig. 5 Paper networks in subset 'Technical options'. On the left, the research front is the result of a bibliographic coupling analysis (similar to Fig. 4). On the right, co-citation coupling visualises the intellectual base. A node is a reference that is cited together with other references. The more often it is cited with other references in the set, the larger the node. Two references are linked if they are cited together. Three key references are indicated: ore[44], bra[45], bøh[46].

Studying the most important papers from the research front reveals that there are several options for decreasing energy consumption through EER. The authors' main purpose is to evaluate the effects of EERs in terms of energy saving, emission reduction and economic viability. The importance of this topic is underlined by the fact that it is addressed by most of the key papers, of which the analysed technical options and their effects are summarised in Table 2.

Table 2 Technical options and their effects as presented in the key papers, obtained by bibliographic coupling in the core area 'Technical options'

Paper	Region	Technical options	Effects
Bojić et al. (2012)[47]	Serbia	Insulation of external wall; lowering of ceiling; thermal insulation of ceiling	Of these, the best single refurbishment measure (in terms of energy savings, investment and investment return) is thermal insulation of the external wall.
Hong et al. (2006)[48]	UK	Cavity wall and loft insulation; introduction of gas central heating system	Cavity wall and loft insulation can reduce the space heating fuel consumption by more than 10%. The introduction of a gas central heating system has no significant impact in reducing fuel consumption.
Chen et al. (2013)[49]	North China	Retrofit of space heating system, roof, wall, windows	Measures are cost effective except window and wall retrofit, which are not economic to conduct separately.
Liu et al. (2013)[50]	North China	Retrofit of external wall, windows, indoor heating system	External wall retrofit makes the largest contribution to energy conservation followed by external window retrofit.
Lloyd et al. (2008)[51]	New Zealand	Retrofit of external walls, windows, floor, ceiling	The average indoor temperature was higher. A small reduction in energy consumption was also found.
Anastaselos et al. (2011) [52]	Germany	Use of radiative heating system	Infrared heating systems can be combined with renewable energies to enhance the building's overall environmental efficiency and significantly improve the thermal comfort.

As expected from the paper network analysis, most of the identified key papers can be assigned to northern China and the UK. Others present findings from studies in New Zealand, Germany and Serbia. Research activities focus on two types of EER, i.e. thermal insulation and retrofitting space heating systems. Thermal insulation measures include the insulation of external walls and ceiling and window retrofits. Despite the fact that retrofitting space heating systems may include the switch to renewable energies such as biomass (pellet stove), ambient and geothermal energy (heating pump) or solar energy (solar thermal system), none of the identified key papers discuss these options in detail. The research focus appears to be on thermal insulation rather than space heating systems or especially space heating systems based on renewable energies. It was found that energy saving, emission reduction and economic viability of EER measures is dependent on different aspects such as

- the type of measure/combination of different measures being carried out;
- the heating behaviour before and after the implementation of measure(s);
- the location (energy prices, climate, etc.);
- the type and current state of the building.

Key references in the intellectual base (displayed in Fig. 5) are from two approaches. The first contains reviews and surveys; the other discusses the results of case studies. Authors of the highest rated reference carried out a survey to "quantify the extent to which variation in indoor temperatures is explained by dwelling and household characteristics" [44]. It was found that temperatures are influenced by property characteristics (age, construction, thermal efficiency) and also by the household number of people and the age of the head of the household. Two other references present the survey results on domestic dwelling temperatures (which is important to assess the value of various energy conservation measures) [53] and on the English house condition [54]. The English house condition survey is a continuous national survey "that collects information about people's housing circumstances and the condition and energy efficiency of housing in England" [55]. This survey is highly rated in all other subsets as well (see Appendix B.1). The second field contains case studies. Branco et al. (2004) examines the difference between the calculated and actual heat consumption of buildings [45]. The authors state that a major difference occurs when the real conditions of utilisation are not taken into account in the calculations. Bøhm and Danig (2004) discuss results from monitoring the heating system and the loading circuit for the production of domestic hot water [46]. The authors suggest to provide tools to help users to analyse the energy consumption of their buildings. Apart from pure data sources, mainly literature from two topic areas is used for current studies on the economic viability of EER measures:

- Literature on indoor temperatures;
- Literature on the difference between actual and calculated energy savings or heat demand

The second topic area is also addressed by papers on the research front [49,50].

The analysis shows that the retrofit of the space heating system, roof, wall and windows are commonly applied renovation measures, which are, in many cases, economically viable. There are indications that measures conducted together have a higher chance to be economically viable. Research also focuses on thermal comfort and the difference between actual and calculated energy savings or heat demand after the implementation of EER measures. Thus, the actual (socio-economic) energy saving potential and profitability of EER measures is lower than generally expected.

4.3 Understanding decisions

Two main clusters were found in the research front on ‘Understanding decisions’, namely implementation approaches and residents’ decision context (see Fig. 6).

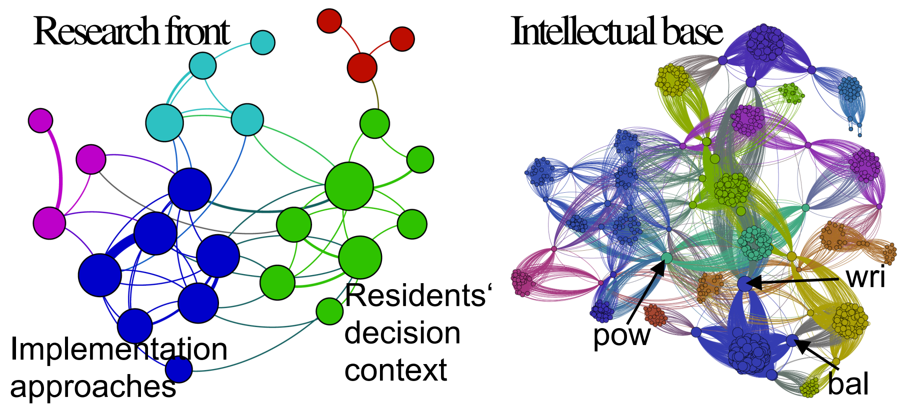


Fig. 6 Paper networks in subset ‘Understanding decisions’. Three key references are indicated: pow[56], wri[57], bal[13].

The first cluster works on the residents’ decision context. Decisions about EERs are dependent on residents’ motivations and, prior to this, barriers, legislative constraints, demographic developments, and so on. Table 3 presents the main motivations and barriers found by Organ et al. (2010) [58] and Zundel and Stieß (2011) [41].

Table 3 Main motivations and barriers regarding EERs as presented in the key papers, obtained by bibliographic coupling in the core area ‘Understanding decisions’

	Motivations	**Barriers**
Economic	An EER • pays back; • increases the home’s value; • reduces energy bills and vulnerability against volatile prices.	Homeowners may • not have the necessary financial resources; • be unwilling to raise a (further) loan; • not be sure, whether the investment will pay off.
Non-economic	An EER • increases thermal comfort, convenience, status, resilience against climate change; • reduces energy demand, environmental impact, risk for future supply problems, and dependency on fossil fuels.	Homeowners may • have the opinion that no (further) refurbishment is needed; • have no time to deal with that topic; • be not interested to do more upkeep than necessary; • be worried that a renovation causes much dirt and stress.

Beside the detection of motivations and barriers it is important to understand the homeowners’ decision-making processes. Zundel and Stieß (2011) point out that homeowners not only consider the additional costs of technical measures to estimate their profitability and do not solely regard their refurbishment as an investment. The authors argue that "refurbishments are the outcome of a broader decision which is shaped by an alliance of economic and non-economic motives and goals” [41]. Crilly et al. (2012) conclude that a comprehensive understanding of the whole process is essential to make informed decisions on the EER of homes. It is inadequate to focus on just one of the various motivations to perform an EER [59]. Vadodaria et al. (2010) point out that “irrespective of cost factors, the perceived benefits and aspirational appeal of carbon-reducing technologies need to outweigh the cost associated with disruption from the perspective of the householder” [42].

The second cluster focuses on approaches to integrate energy efficiency measures in refurbishments and claim that an improvement of policy instruments is necessary to trigger activity. Konstantinou and Knaack (2011, 2013) propose a set of different refurbishment options systematically organised in a “toolbox”. By defining the impact of different possible choices, the decision-making process about refurbishments is supported and incorporated into the aim of integrating energy efficiency into refurbishment strategies [60,61]. The other key papers were also identified in the core area ‘Incentive Instruments’. Since they provide greater insights concerning this matter, we present their main findings in the corresponding section.

Key references cover a wide range of topics such as presented in table 4. Contrary to our expectations, the intellectual base contains no prominent literature on decision making. This indicates that there is no shared basis on decision making addressing this issue. Rather, the intellectual base covers the topic in general. This was confirmed by a scan through the other references in the intellectual base.

Table 4 Main conclusions of key references in the intellectual base, obtained by co-citation coupling in the core area ‘Understanding decisions’

Paper	Subject matter	Main conclusions
Power (2008) [56]	Demolish or refurbish older housing?	Refurbishment of older housing induces major social, economic and environmental benefits and is preferable to demolition.
Tommerup and Svendsen (2006) [62]	Energy saving potential of EERs in Denmark	Energy performance upgrades offer a great (profitable) energy saving potential within the residential building stock.
Balaras et al. [13]	Priorities for EERs in the EU	The most effective measure in terms of energy savings is the insulation of external walls.
Wright (2008) [57]	Factors influencing energy use	Energy use in dwellings is influenced by a complex interaction between built form, location, energy-using equipment, occupants and the affordability of fuel.

Our review of the research front shows that decisions on EERs are affected by several economic and non-economic motivations and barriers. Researchers still intend to gain a deeper understanding of the decision-making processes of homeowners regarding EERs. The intellectual base indicates that the research on understanding the decisions is in its infancy, because there is limited underpinning of decision making regarding EERs.

4.4 Incentive Instruments

Clusters from the research front on ‘Incentive instruments’ form around papers from two main authors, Ray Galvin (University of East Anglia, UK) and Jinlong Ouyang (Sichuan University, China) (see Fig. 7).

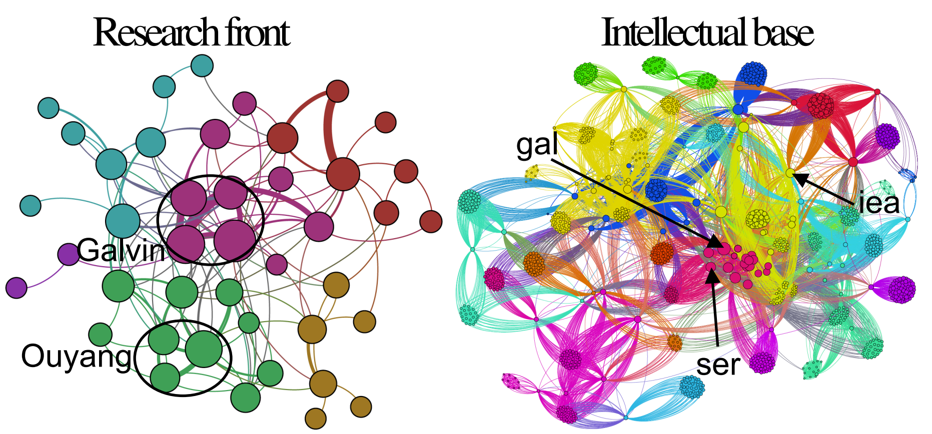


Fig. 7 Paper networks in subset ‘Incentive instruments’. Three key references are indicated: gal[63], ser[64], iea[65].

Identified key papers and references evaluate existing incentive instruments and give recommendations for the future. Table 5 presents the authors’ assessment of existing incentive instruments.

Table 5 Evaluation of existing incentive instruments as presented in the key papers and references, obtained by bibliographic and co-citation coupling in the core area 'Incentive Instruments'

Paper	Region	Incentive Instrument	Evaluation
Weiss et al. (2012) [66]	Germany	Regulatory instruments; subsidy programmes; communicative instruments	These, for Germany most important measures for motivating homeowners to pursue energy-efficient retrofitting, have brought only little success. Existing instruments do not adequately address the barriers in homeowners' decision making.
Galvin (2010) [63]	Germany	Progressive regulation for higher renovation standards; subsidies only for projects that go beyond a minimum standard	These policies may not work out well in the future. Costs of renovating to high standards rise exponentially while the amount of additional energy saved rises only a small amount.
Watts et al. [67]	England and Wales	Energy Performance Certificates	Energy Performance Certificates are a mandatory requirement for all dwellings sold or rented in the region, but have had little impact on decision making or price negotiation so far.
Grösche and Vance (2009) [68]	Germany	Programs that provide subsidy for retrofits	The effectiveness of these programs may be undermined by free-riders, i.e. house owners receiving the subsidy which would also have renovated without the subsidy.
T'Serclaes (2007) [64] and IEA (2008) [65]	EU, USA, Japan	Policy packages which seek to address multiple financial barriers at the same time	Such policies are likely to be quite effective.

Several inventive instruments such as regulations or subsidies are applied to trigger more EER activity. The authors point out that they have brought only little success so far and attempt to understand why that is the case. One explanation that the literature provides, is that they do not adequately address the barriers in homeowners' decision making.

We have made a structured overview of the recommendations regarding incentive instruments from the key papers and references. They can be clustered around three approaches: either they intend to enforce existing instruments, to increase the economic viability of measures, or to introduce new approaches (see Table 6).

Table 6 Recommendations of identified key papers and references regarding incentive instruments, obtained by bibliographic and co-citation coupling in the core area 'Incentive Instruments'

Approach	Recommendation
Enforcement of existing instruments	• Introduce random audits to improve the implementation and enforcement of existing regulatory standards and to make better use of refurbishment opportunities [66]; • Better communicate the benefits of financial aid mechanisms for improving energy efficiency [67]
Increase of economic viability	• Increase energy prices and provide subsidies for renovating aging residential buildings (in China) [69]; • Expand financial support instruments targeted at home-owners willing to achieve a high standard of energy efficiency as well as those meeting lower standards [66]; • Governments need to create more favourable conditions for energy efficiency investments [65]
Introduction of new approaches	• Emphasise on reasons for EERs measures other than economic viability [70]; • Take into account other reasons for low levels of renovation activity (e.g. costs) and individual-based explanations of behaviour (e.g. no motivation) and carry out in-depth analyses into social practises of households [71]; • Increase awareness of co-benefits and cost dynamics of energy efficiency investments of decision makers in the real estate sector, politics and administrations [72]; • Consider social criteria [66]; • Introduce Public-Private-People Partnership (4P) into redevelopment processes. 4P can lead to a situation where EER is affordable and people can choose between several renovation and finance options [73]

The first two sets of approaches aim to improve existing incentive instruments by increasing implementation rates, expanding their scope and by changing the economic context in which they take place. The last set contributes approaches that mainly address non-economic motivations and barriers. The literature also suggests that additional research is needed that addresses policy design that incorporates relevant non-economic factors in the decision making of homeowners.

As hypothesised, several instruments are available to motivate homeowners to improve the insulation of their homes, but their success rate is rather low. Confirming Section 4.4's findings, the literature suggests that the success of policies depends on how homeowners' decision making is taken into account.

4.5 Models and simulation

In the research front on 'Models and simulation' we found a cluster on statistical models as well as strongly interconnected clusters on behaviour and economic viability (see Fig. 8).

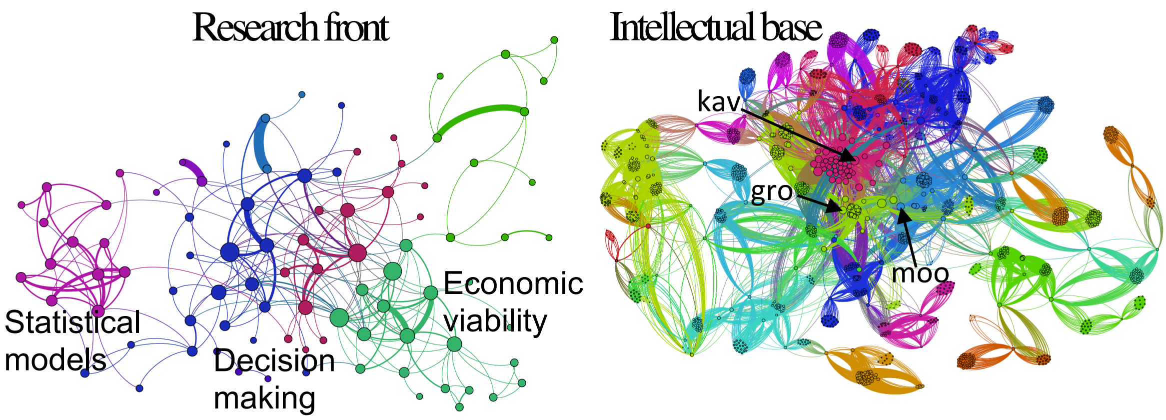


Fig. 8 Paper networks in subset 'Models and simulation'. Three key references are indicated: kav[74], gro[68], moo[54].

The main conclusions of the key papers are presented in Table 7. By examining the abstracts of the most important papers from the research front, we identified two clusters of models, which is in line with the results of our paper network analysis (see Fig. 8). The first group focuses on economic viability whilst the second contains models addressing homeowners' decision making regarding EER measures.

Table 7 Main conclusions of the identified key papers, obtained by bibliographic coupling in the core area ‘Models and simulation’.

Paper	Cluster	Subject matter	Main conclusions
Amstalden et al. (2007) [75]	Economic viability	Assumed future energy prices	Present Swiss policy pushes investments for energy-efficient retrofitting to profitability. Assumed future energy prices are very important for the predicted investment profitability.
Galvin and Sunikka-Blank (2012) [76]	Economic viability	Fuel price elasticity of demand	The inclusion of fuel price elasticity of demand into models lowers the net present value and lengthens the payback time of retrofit measures. CO_2 saved over the technical lifetime is lower than anticipated.
Ouyang et al. (2009) [77]	Economic viability	In fact and simulated energy demand	There is a great discrepancy between in fact and in thermal simulation of heating and cool loads. Therefore, the investigation of the factual energy consumption of the subject building is very important to predict accurately the energy-saving effects and financial benefits of measures.
Ouyang et al. (2011) [77]	Economic viability	Life cycle cost	Building energy retrofits in China would lead to less energy consumption meant less environmental load and would reduce the tight pressure from the international environmental organizations. Occupants would enjoy a more comfortable indoor environment and avoid energy costs.
Organ et al. (2013) [58]	Decision making	Homeowners’ motivations	Differing internal factors, contexts and the dynamic nature of owner-occupier motivation have to be taken into account to shape national and local policy and information campaigns.
Charlier and Risch (2012) [78]	Decision making	Environmental public policy measures	The effectiveness of a policy is stronger if it is combined with another. However, the redundancies of policies can lead to inefficiency.

Models in the cluster on economic viability explore different factors that influence the estimated economic viability of EERs. The authors point out that some of the factors, such as assumed future energy prices, price elasticity, and the difference between expected and realised energy demand, are crucial in the analysis of EERs, for instance in terms of sensitivity of the models’ outcomes.

Two key papers address homeowners’ decision making. Organ et al. (2013) present a motivation model for EERs in owner-occupied housing; Charlier and Risch (2012) consider a variety of household investment decisions. Other top rated papers, that focus on behaviour, analyse the influence of future energy price expectations and the role of environmental concern [79–81]. None of the identified papers provides a model of the process of EER decision making of homeowners.

Various reviews prominently underpin the models and simulations [74,82–84]. These reviews are not on decision making regarding EER measures, but on building stock models, rebound effects, discount rates, and differences between measured and theoretical energy savings. In addition, the intellectual base contains papers on homeowners’ behaviour, examining determinants of heating expenditures and the willingness to pay for energy saving measures and energy conservation [68,85,86].

5 Conclusions

We analysed a set of 449 peer-reviewed articles and conference proceedings on energy-efficient renovations (EER) as well as their ~7,000 references in order to identify the obstacles involved in increasing the adoption of EER measures and what has been done to address the problem so far. We conclude that the literature on energy-efficient renovation gained considerable momentum in the last decade, but lacks a deep understanding of the uncertainties surrounding economic aspects and non-economic factors driving renovation decisions of homeowners.

We have performed a keyword analysis to identify appropriate terms for papers in the field, visualised and analysed the networks of the research front and intellectual base. We have shown that bibliographic coupling can be used to identify clusters of papers with a related subject matter within the topic of EER in buildings. Clusters form around specific topics (e.g. behaviour or economic viability), geographical areas (i.e. China, Ireland and the UK), methodologies (e.g. statistical models), despite the fact that none of these were included as keywords in our keyword-based search.

We studied key papers of four core areas to evaluate our hypotheses (see Section 1) on technical options, understanding decisions, incentive instruments, and models and simulation.

Hypothesis I – Technical options and economic viability
The literature indicates that the (socio-economical) energy saving potential and profitability of EER measures is lower than generally expected. Nevertheless, the key papers evaluating the effects of EER options on energy savings, investment return and thermal comfort confirm that EER options are cost effective in most cases. Some indicate that measures conducted together have a higher chance to be economically viable [47,49]. There is considerable attention for the difference between expected and realised energy savings or heat consumption. This effect leads to underestimates of renovation's pay back times. One reason for this bias is the fact that heat consumption levels also depend on energy expenditures, leading to less energy consumption in poorly insulated and higher energy consumption in thermally refurbished houses than predicted.

Hypothesis II – Decision-making processes and incentive instruments
Individuals perform EERs if various wants and needs are met [41]: the homeowners' decision to renovate is shaped by an alliance of economic and non-economic goals such as reducing energy bills, raising comfort, and reducing their environmental impact [58]. The research on understanding the decisions regarding EERs is just emerging, which is, in our analysis, illustrated by the way in which the research is grounded.
Numerous papers focus on the evaluation of incentive instruments that motivate homeowners to thermally refurbish their homes and give recommendations for making improvements. The literature shows that existing instruments have brought only little success and recommend to enhance existing instruments and to consider new approaches that take into account the decision-making processes of homeowners.

Hypothesis III – Models and simulation
The literature focuses on modelling the economic viability of renovations and the

potential for energy savings and CO_2 reduction. However, some of the factors that influence the estimated economic viability of EERs are not taken into account, which leads to biased results, overestimating the merit of EERs. In addition, non-economic factors are typically ignored. None of the key papers in this area present models of the process of heterogeneous individual homeowners' decision-making regarding EERs.

Clusters

Our analysis led to unexpected findings in the way in which clusters appear in the citation networks. One surprise is a cluster on statistical models which emerged in both the network analysis of the full paper set as well as the subsets. This finding suggests the existence of another research front, and should be taken into consideration when focusing on questions addressing related issues. Another is the focus on geographical areas, which indicates that both the intellectual base as well as the research front may well be specific to regions. This indicates that there are ample opportunities for research on EERs bridging cultures.

Modelling motivations for renovations

The analysis resulted in an overview of the motivations for homeowners to do renovations. Economic aspects are found throughout the literature. A variety of other motivations could be further explored. An approach for future research is to use simulation which maps the decision-making process of homeowners on EERs for their homes, exploring heterogeneity, perceived economical and non-economical motivations and barriers, and social impacts in different socio-spatial structures. The main factors that influence the current low take up rates in EER may be elucidated with such a model. Additionally, it may result in refining existing instruments or developing new innovative instruments that would address the problem. This could save a considerable amount of time and resources needed to meet climate protection targets.

We are aware that, as with any analysis, the data used will not cover everything there is to say about EERs in buildings. We aimed at a broad analysis by including a relatively large number of papers and explored both their content and structure. We have identified the most important papers within this field of research and analysed them, which corresponds to the methodology described by Allen et al. (2009), who state that tools linking expert peer reviews with quantitative indicators, such as citation analysis, are useful when attempting to assess the importance of research papers [87]. We hope that our analysis leads to a better understanding of the literature on EERs, that it may enable cross-fertilisation of research, and, at the end of the day, that it may inspire the development of appropriate policies that enable us to reach ambitious climate protection targets.

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Appendix A: Data preparation

A.1 Tool to standardise different data formats
In order to create a look-up table - a tool for automatically standardising the format of the same bibliographic information in a reproducible way - a list of the different paper designations was uploaded to and processed using *Google Refine*. Next, two columns from the list were created entitled "original" and "preferred". Within the "preferred" column, different clustering methods were applied to find groups of (often slightly) different patterns used for the same bibliographic information. Since it is likely that this method can also cluster false positives all suggestions to merge potentially identical bibliographic information had to be checked manually (see Table A.1).

Table A.1 Example for clustering using Google Refine

Values in Cluster	New Cell Value
1) "corrado, v. uncertainty and sensitivity analysis for building energy rating (2009) j build phys, 33, pp. 125-154" 2) "corrado, v. uncertainty and sensitivity analysis for building energy rating (2009) journal of buildings physics, 33 (2), pp. 125-154 "	1) and 2) "corrado, v. uncertainty and sensitivity analysis for building energy rating (2009) journal of building physics, 33 (2), pp. 125-154 "

Since our main interest was the content of papers and their references, regardless of the specific circumstances of their publication, we also merged the following bibliographic information:

- Different publication statuses, for example: conference proceedings, submitted, in press, published, updated edition;
- Different parts, chapters, section of pages;
- Reports, balances, reviews, statistics from different years.

The resulting table of "original" and "preferred" patterns of bibliographic information was used to prepare the data for the analyses. For this purpose, another script was used at different stages within the implementation of the citation network analysis. In the first step, the script deletes rows within the table where the patterns of both columns (original and preferred) look alike. After performing this step, the look-up table is ready, containing 1,095 rows in our case. Hereafter, the script loads the data from the file to be processed and looks up the patterns of the 'original' column and replaces them with the patterns of the 'preferred' column from the look-up table.

The procedure described above is necessary because *Gephi* (used to visualise and explore the paper networks) only recognises the occurrence of equal paper designations and references if the patterns are exactly the same.

A.2 Scripts to implement citation analyses

Bibliographic coupling

Before we were able to couple papers using the same references, it was necessary to accomplish two prior steps: 1) generation of an edge list of direct citations; and 2) use of the look-up table to standardise the format of same bibliographic information.

The script used to produce an edge list of direct citations takes the references of the different papers and places them separately into a column next to the duplicated paper designation. The script to process the look-up table (see Appendix A.1) is then used to standardise the format of same bibliographic information within that list.

Finally, the script that couples papers with the same references was executed. The script initially creates a separate list of references and deletes duplicates. Afterwards, it reads the list line by line and looks for equal patterns within the edge list of direct citations. If an equal pattern is found, the pattern aside (the paper designations) is copied to a temporary file. The temporary file later contains one or more (if a reference is cited by more than one paper) paper designations. Finally, a double loop is used to combine and add each combination of these patterns to the final edge list.

Co-citation coupling and analysis

For co-citation analysis, editing the data started with splitting the complete file into files organised according to the pattern of bibliographic information. In these files a loop with different steps was executed:

1. Store the paper designation in one file and a list with the references in another;
2. Separately link the (duplicated) paper designation to the paper references and store them in an edge list;
3. Finally extend the edge list through a list of all possible combinations of the references, using a double loop.

Besides performing the complete co-citation analysis, results of co-citation coupling were collected. For co-citation coupling, the combinations of references were not linked to the paper designations. After performing this procedure for all patterns of bibliographic information, the script for the look-up table was executed to standardise their format.

Appendix B: Complementary results

B.1 Overview on key papers and references

The following table gives an overview on the several key papers and references identified by examining the different subsets. Some were identified through bibliographic coupling as well as co-citation coupling within our different subsets (see Table B.1, written in bold).

Table B.1 Key papers in different subsets identified by different methods

Bibliographic Coupling				**Co-citation Coupling**			
Technical options	Understanding decisions	Incentive instruments	Models and simulation	Technical options	Understanding decisions	Incentive instruments	Models and simulation
[49][47] [48][50] [51][52]	**[56][58][67] [73][66]**[41] [42][59][60] [61]	**[63][68] [67][73] [66]**[69][70] [71]	**[49][75] [58][68]** [76][77][77] [78]	**[54]**[44] [53][45] [46]	**[56][54][75] [74]**[57][13] [62][88][89]	**[63][54]**[64] [65][72][90] [91][92]	**[54][68][74]** [86][82][83] [84][85]

Most overlaps occurred between the subsets ‘Understanding decisions’ / ‘Incentive instruments’ and ‘Understanding decisions’ / ‘Models and simulation’. This is not surprising because research on modelling and incentive instruments also requires knowledge of homeowner motivations, their decision-making processes and possible barriers.

B.2 Most related papers

After listing the links between papers at the research front by thickness, it was not surprising to find that authors reuse their references. An analysis showed that 80% of the papers which share more than 5 references have at least one same author. For the top 3 most related papers, see Table B.2.

Table B.2 Top three most related papers (bibliographic coupling, full paper set)

Node I	**weight**	**Node II**
Clinch et al. (2001), modelling improvements in domestic energy efficiency, environmental modelling and software	16	Clinch et al. (2001), cost benefit analysis of domestic energy efficiency, energy policy
Sunnika and Galvin (2012),introducing the prebound effect: the gap between performance and actual energy consumption, building research and information	15	Galvin and Sunikka (2012), including fuel price elasticity of demand in net present value and payback time calculations of thermal retrofits: case study of German dwellings, energy and buildings
Theodoridou et al. (2011), statistical analysis of the Greek residential building stock, energy and buildings	15	Theodoridou et al. (2011), assessment of retrofitting measures and solar systems' potential in urban areas using geographical information systems: application to a Mediterranean city, renewable and sustainable energy reviews

Through co-citation coupling we expanded our analysis to the intellectual base, identifying the key references from almost 7,000 different references – including ‘grey literature’ not covered by *Scopus*. A detailed analysis of the links between two references revealed that frequently co-cited references are mainly recurring works such as data books and surveys of different years.

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