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Understanding the uneven diffusion of building-scale renewable energy systems: A review of household, local and country level factors in diverse European countries

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ABSTRACT

This review focuses on renewable energy technology deployment in residential buildings, which is part of current targets to develop net-zero-carbon buildings in Europe and to promote the deployment of renewable energy. We focus on the adoption of four technologies: heat pumps, solar photovoltaics, solar thermal systems for domestic hot water and space heating, and advanced biomass heating. While there are several studies on households' investment criteria, a research gap exists because building owners across Europe are quite diverse, and the European markets exhibit different stages of maturity. This article conducts a critical review of the literature on the diffusion of building-scale renewable energy solutions in order to answer the following questions: (1) to what extent can findings from studies on household adoption criteria be generalized from one country to another? and (2) what insights does the literature offer on factors that might explain the differences in adoption patterns between European countries?

1. Introduction

Buildings are increasingly key to decarbonizing the economy. Improvements to the energy efficiency of building envelopes and systems are the primary means envisaged for such decarbonization [1,2]. However, in existing buildings, renewable heating, cooling and power are likely to play an important complementary role to energy efficiency in bringing buildings closer to net-zero energy or carbon status [3,4] given the fact that the building stock is very long-lived [5], whereas building systems have shorter lifespans and are thus renewed more rapidly [6]. As a result, the adoption of new heating, cooling and power production technologies in buildings is of increasing interest for both policy makers and companies marketing renewable energy solutions for buildings.

This review focuses on renewable energy technology deployment in buildings, which is part of current targets to develop net-zero-energy or net-zero-carbon buildings in Europe, but also to promote the deployment of renewable energy [7]. It concerns the small-scale deployment of renewable energy in heating, cooling and power production in or near buildings to reduce imported energy, as well as to contribute to the share of renewable energy in the energy mix. From this perspective, the following technologies are most relevant [6,8–10]: heat pumps, solar photovoltaics, solar thermal systems for domestic hot water and space heating, and biomass heating (especially advanced biomass central heating systems such as wood pellet boilers). In the following, these technologies are referred to as "building-scale renewable energy systems".

Several studies investigate the economics of investing in building-scale renewable energy systems [11–13]. However, building owners' decisions are rarely driven by sophisticated financial analyses of alternatives [14,15]. The European building stock is owned by millions of diverse building owners, with different perspectives on investing in technical upgrades of their properties. A particularly problematic category consists of private homeowners (owners of single-family homes or apartments), who own most of the European building stock, but often lack technical expertise and capital to make investments, and whose investment criteria and investment environments are heterogeneous and difficult to predict.

Several recent studies have investigated factors influencing household adoption of building-scale renewable energy solutions [16,17], and there are already a few reviews focusing on motivations and barriers for adoption in particular countries [18]. However, we are not aware of any studies that systematically examine similarities and differences in adoption criteria across European countries or across technologies. This is a research gap, since the adoption levels of building-scale renewable energy technologies differ widely across

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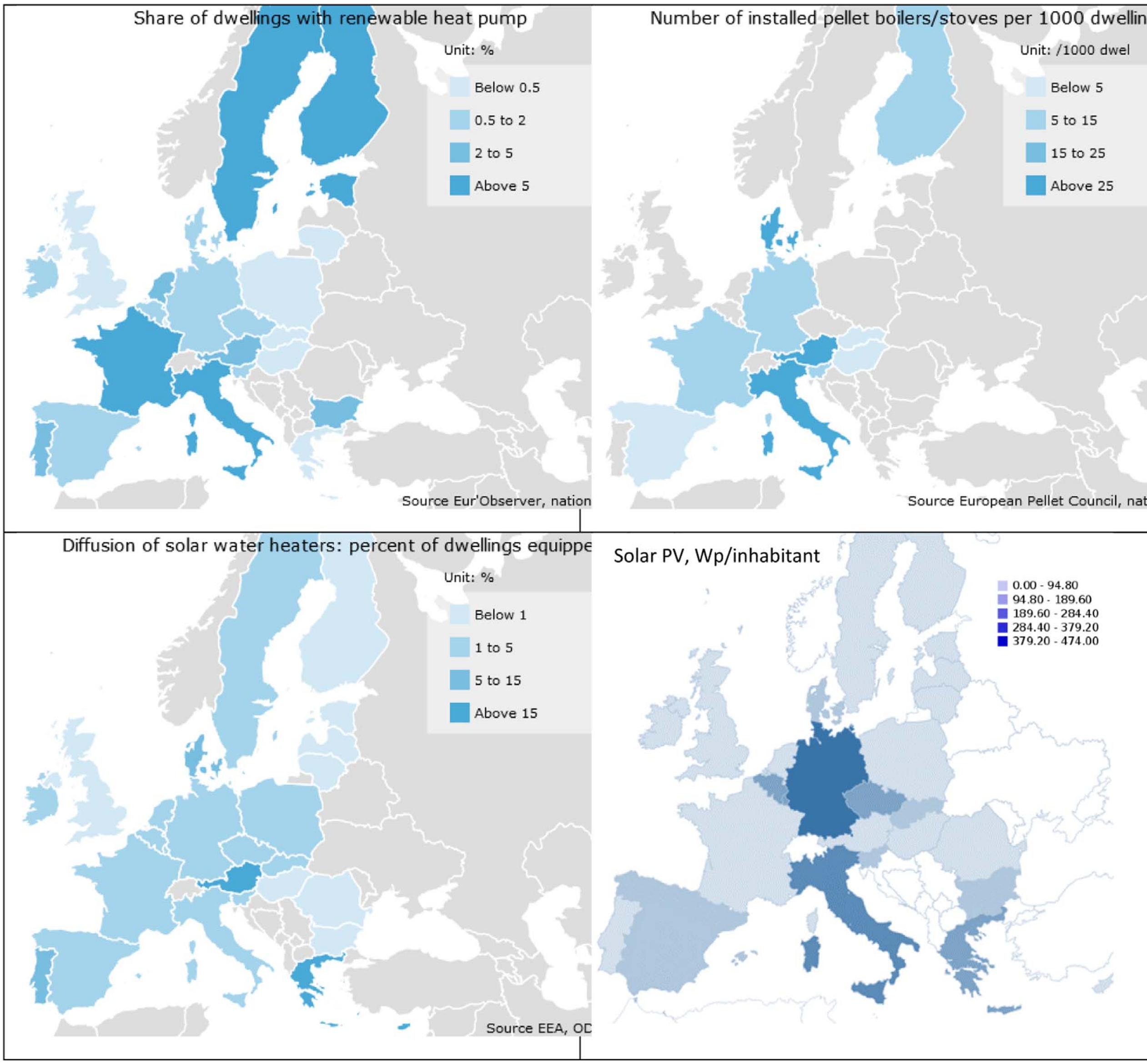

Fig. 1. Levels of market penetration of four building-scale renewable energy systems: (a) heat pumps, (b) pellet boilers, (c) solar collectors and (d) PV panels. Sources (a)–(c): Odyssee based on Eur'Observer, European Pellet Council and EEA, (d) Eur'Observer visualised via Datamaps.eu.

Europe (Fig. 1) in a way which is not readily explained by geography alone [11,19–21].

The uneven uptake of renewable energy 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. The institutional and historical embedding of different technologies in specific local and country contexts is likely to be relevant for building owners' decision making, since driving forces and barriers can also be different at different stages of the diffusion of innovative solutions [8]. Unlike previous reviews, we separately examine literature pertaining to the importance of factors in the households' country context and local context, which has not been addressed in previous reviews on the adoption of building-scale renewable energy systems.

The aim of the current review is to investigate the literature concerning the diffusion of building-scale renewable energy solutions in order to answer the following questions arising from the uneven uptake of building-scale renewable energy solutions in Europe:

(1) To what extent can findings from studies on household adoption criteria be generalized from one country to another?

(2) To what extent does the existing literature offer useful insights on household factors and factors in the local and country context that might explain the differences between countries?

In the following, we describe the material and methods used. The first part of this review (Section 3) examines household-level studies of which factors influence investments in building-scale renewable energy systems. Based on this and additional material, the second part (Section 4) examines factors in the householders' local context that have been found to influence investments. The third part (Section 5) focuses on the country context, and alongside the obvious factors of geography, policy and markets, examines existing literature on the role of other contextual factors, such as professional and expert communities, the media and social movements. In our discussion and conclusions (Section 5), we then identify factors that are worth considering when researching and promoting building-scale renewable energy systems in European residential buildings. We develop propositions for quantitative research and ideas for qualitative research on how household, local and country contexts are interconnected.

2. Material and methods

We conducted a critical review [22] of the relevant literature, i.e., our aim is to not only describe, but to reorganize and produce a new synthesis of the literature. We have used a structured keyword-based search to gather papers, citations, and authors in the fields of "renewable energy", "solar energy", "solar photovoltaic", "solar thermal", "pellet boiler", "heat pumps", "micro-generation", "solutions" and "buildings" combined with key words such as "adoption", "acceptance", "decision making" and "choice", using Google Scholar and, in particular, its "citing articles" function. We especially went through articles in academic journals such as *Energy Policy*, *Renewable Energy*, *Energy and Buildings*, *Built Environment*, *Renewable & Sustainable Energy Reviews, Environment and Behaviour* and *Ecological Economics*. Furthermore, we reviewed conference proceedings such as the *eceee Summer Studies* and publications of European and international organizations such as the *OECD, European Commission* and its research programmes, and the *IEA*. We also surveyed relevant articles in books. Additionally, relevant statistics (Eurostat, EurObserver, Odysee Mure) have been surveyed. Only English-language literature has been considered.

This article search rendered a set of 27 studies from 2004 to 2014 focusing on household decision making, acceptance and adoption of building-scale renewable energy systems in Europe. Since the focus is on household investments in the selected technologies, studies focusing only on willingness to pay for renewable-based electricity delivered over the grid [23] were excluded. The findings of these articles were then compared to identify similarities and differences across studies. These articles, and a supplementary set of 61 qualitative studies or studies focusing on particular aspects relevant to the adoption or diffusion of these technologies were used to develop additional categories of relevant contextual factors influencing household decision making on the local and national scales, which were then populated by additional searches for literature pertaining to "geography", "policy", "market", "media", "expert", "peer effect" and "social movements" combined with the descriptors for the relevant technologies.

3. Factors influencing household adoption of building-scale renewable energy systems

Table 1 presents an overview of recent (2004–2014) studies of factors influencing building owners' decision making concerning building-scale renewable energy systems across European countries. A factor worth noting is the great diversity in the research designs. There are two basic approaches. One is to explain the existing system choice via various factors, i.e., to uncover drivers and explanatory factors for the choice of a particular system. The other is to ask people what they would choose or prefer or how much they would be willing to pay for particular systems (e.g., choice experiments). Additionally, people may be asked to evaluate their own decision making factors [24]. The design of the study influences the results, since existing questionnaire studies are based on diverse theoretical propositions (e.g. rational investment decision, attitude-behaviour models, innovation diffusion), which influence the choice of items examined.

Moreover, the level of sophistication of the research designs varies from sophisticated models with randomized sampling to simple exploratory surveys with purposive samples using correlations or means tests for analysis. All relevant studies found pertaining to the EU-28 have been included in Table 1, in order to capture maximum variation in country contexts and types of technologies analysed. Relevant studies from outside the EU, e.g. [25,26], are excluded from the table, but considered in the subsequent analysis. In the following, we briefly examine some of the main findings from this research in order to identify similarities and differences across countries and technologies, as well as to identify research gaps and pointers for contextual factors influencing households' investment behaviour.

3.1. Focus on socioeconomic, demographic and psychographic factors

The most frequently examined factors in the literature on household adoption of renewable energy systems include socio-economic (income, costs), psychographic (attitudes, knowledge) and demographic (age, household type) factors. We briefly review the commonalities identified in the studies presented in Table 1.

Economic factors are the ones arising most consistently from studies of diverse technologies (solar PV, solar thermal, heat pumps and biomass heating systems) and across countries. When examining the influence of socio-economic factors explaining adoption of willingness to adopt, income is the factor that arises most consistently, though there are studies where income does not make a difference or even where lower-income households are more interested in technologies that can save energy costs [17]. Moreover, some studies suggest that the influence of income on propensity to invest is not linear: income increases the propensity to invest significantly when moving from low to middle income, but much less after that [18,27]. Unfortunately, few studies have investigated the influence of property values or access to capital, which might be more closely targeted measures for households' capacity to invest in new systems [14].

When decision criteria or barriers to adoption are investigated, the cost or affordability of the new system is usually a key issue [18,26]. Some studies have made sophisticated analyses of consumers' willingness-to-pay for various systems. The studies - which reflect prosperous West and North European contexts - indicate that single-family home owners' required rates of return for heating systems vary from 12% [28] (heating systems in general), to 16% (for ground source heat) and 22% (for wood pellets) [29] to 34% for diverse renewable solutions in the UK [30]. There are differences both between countries and among the different solutions. It seems that when the solutions are perceived of as innovative and risky, mainstream consumers require higher rates of return than for more conventional systems. On the other hand, householders rarely actually calculate returns on investments [14]. For example, Bjørnstad [26] has shown return on investment did not in practice make a difference for Norwegian householders' satisfaction in pellet boilers or heat pumps; rather, consumers used the simple but easily observable proxy of electricity price when evaluating their investment.

As concerns socio-demographic factors, the impact of age appears to be non-linear, just like that of income: most studies find that older households are less likely to adopt new technologies or invest in building-scale renewable energy systems, whereas some suggest that middle-aged [31] or older households [32] can be forerunners in investing in novel technologies. This can depend on the age categories used: it seems likely that age often correlates with income and accumulated wealth up until retirement, whereas after retirement there are significant barriers and disincentives to invest [18]. Some of the more thoughtful, often qualitative studies take into account that the choice of a heating system is not made in a void, but in relation to the current situation of the building owner, the condition of the building, existing systems in place, as well as the available alternatives [33].

Education, however, appears to be more consistently linked with a propensity to adopt renewable energy systems, especially ones that are innovative in their contexts, such as ground-source heat pumps in Greece [17] and pellet boilers in Spain [34]. Some studies have found educational specialization to be influential, with engineering and environmental specializations linked to a higher propensity to adopt [17,34]. The picture concerning environmentalism as a major driver for investments is more mixed, suggesting it is country- and technology-dependent. Some studies find a significant influence [35,36], whereas others do not [18,27].

3.2. Differences among technologies

The most obvious difference between the four technologies is that of

Table 1
Studies on factors influencing household adoption of building-scale renewable energy systems.

Type of solution	Coun-try	Type of owner	Factors identified as influencing acceptance and adoption	Reference
Renewable heating systems	DE	diverse residential	Lifestyle: high-income, young, educated and unconvenional "modern performers" were more likely to prefer renewables (especially solar heat and district heat) than the middle class	Gröger et al. [58]
Renewable vs. fossil heating systems	DE	single-family home owners	Factors influencing choice: environmentalism (pellet boiler), economic aspects, practical issues (availability, storage, etc.)	Decker et al. [35]
Renewable vs. fossil heating systems	SI	diverse residential	Rural households more likely to use solid fuels or oil; urban households gas. Socio-economic and demographic variables do not explain choice of green heating system (solar or heat pumps), but region does to an extent	Zoric and Hrovatin [37]
Renewable vs. fossil heating systems	FI	detached home-owners	Overall preference for groundsource heat and district heat. Loyalty to existing heating system creates choice inertia. Criteria depend on system, but initial cost, operating cost, reliability, fuel price stability and environment important.	Rouvinen and Matero [29]
Renewable heating systems	SE	single-family home owners	Price of electricity, investment subsidies and personal recommendations main motivator; cost of heating, investment costs and functional reliability main concerns	Mahapatra et al. [38,50]
Renewable heating systems	DE	diverse residential	Costs aspect, attitude toward heating system, government grant, independence, environmental concern, comfort, peer influence (some of these differently for different systems)	Michelsen and Madlener[36]
Renewable heat and power	UK	diverse residential	Choice experiment/WTP: initial cost dominant (payback time of 3–5 years), recommendations by engineers and friends would influence choice, concerns: disruption, storage space Age does not influence WTP for boiler, but does influence discretionary investment like PV panels.	Scarpa and Willis [30] Willis et al. [42]
Renewable heat and power	UK	'green' consumers	Older middle-class people pioneers, drivers are savings and environment, barriers price as well as technology-specific barriers	Caird et al. [32]
Renewable heat and power	IE	home owners	Stated preference/WTP: payback time acceptance varies by technology (pellet boilers 7 yrs, solar PV 8.5 yrs, micro wind 10 yrs., solar thermal 13 yrs.) Energy cost savings, independence and environment most important benefits	Claudy et al. [60]
Renewable heat and power	EL	diverse residential	Middle-aged, highly educated people are more likely to adopt, income influences adoption positively	Sardianou and Genoudi [31]
Renewable heat and power+energy efficiency	FR, NL, ES, SE (+non-EU)	diverse residential	Home ownership, detached house, membership in NGO and medium income or above increase propensity to invest, age has tech-specific impact.	Ameli and Brandt [27]
Heat pumps (several types)	UK	social and owner-occupied	Role of surveyor, installers, availability of alternatives, availability of sufficient electric power, installation and maintenance issues, affordability, comfort	Owen et al. [39]
Ground source heat pumps	UK	mostly single-family home owners	Drivers: carbon dioxide emissions, fuel bills, lack of access to gas grid, compatibility with existing building systems, well informed; Concerns: Initial cost, performance, reliability, disruption to garden	Roy et al. [40]
Ground source heat pumps	EL	mainly single-family home owners	Drivers: Educational level and awareness of GSHPs, lower incomes. Barriers: Concerns over lifespan, energy consumption, operational security, installation costs and disruption	Karytsas and Theodoropolou [17]
Air-source heat pumps	DK	single-family home owners	Drivers: Electric resistance heating as original heating system, financial savings, energy savings, improve comfort, reduce pollution	Christensen et al. [41]
Wood boilers	UK	mostly single-family home owners	Drivers: carbon dioxide emissions, fuel bills, lack of access to gas grid, own wood available. Concerns: purchase price, effort to source and use fuel, incompatibility with building system, lack of space, reliability	Roy et al. [40]
Pellet boilers	ES	diverse residential	knowledge, economic factors, education, subsidies and compatibility with space and practices	García-Maroto et al. [34]
Solar thermal	UK	mostly single-family home owners	Drivers: carbon dioxide emissions, fuel bills, low risk, affordability; Concerns: Initial cost, payback, relative advantage, reliability, incompatibility with building systems	Roy et al. [40]
Solar thermal	DE	solar owners and non-owners	Higher propensity to adopt solar in new houses and with new heating systems, in regions with greater geographic suitability and due to other types of clustering	Mills and Scheich [64]
Solar thermal	DE	solar owners and non-owners	Different drivers along the diffusion curve: Owners wealthier and more ecologically motivated, peer example important for those 'planning' to adopt, knowledge and environmental concern important for those 'interested'	Woersdorfer and Kaus [56]
Solar thermal	EL	diverse residential (+others)	High cost, rental home, other priorities, high payback and difficult installation main barriers, cost reductions, self-sufficiency, reliability and quality of life main drivers	Sidiras and Koukios[24]
Small self-assembly micro-generation (solar, wind)	SE	single-family homeowners	Drivers: environmental consciousness, set an example to others, or to protest against "the system" and achieve a degree of self-sufficiency.	Palm and Tengvard[57]
Solar power	UK	single-family homeowners	Different for 'early adopters' (environmentally driven) and 'early majority': for the latter, costs, cost effectiveness and aesthetics limit adoption	Faiers and Neame[54]
Solar power	NL	PV adopters	Environment, subsidies, independence, information meetings and knowing other adopters main influences	Jager[66]
Solar power	DE	home-owners	Status, self-sufficiency, financial benefits and subjective norms major drivers	Korcaj et al.[51]
Own power (unspecified)	NL	diverse residential	Environmental concern, affinity with technology, affinity with energy and poor perceived reputation of energy companies main drivers for intention to produce own power. Older households less likely to want own power.	Leenheer et al.[55]

heating systems vs. auxiliary systems like solar water heaters and solar panels. It makes sense that issues of operation, comfort and convenience are highlighted in studies concerning pellet/log boilers, heat pumps and heating systems in general [17,29,34–41]. Moreover, studies that address both types of systems suggest that investment criteria for 'discretionary' systems are different from criteria concerning 'necessary' systems such as heating systems, which must be replaced when the old system reaches the end of its life [42]. However, expectations toward heating systems may be quite different in different countries. In some countries and for certain age groups, centers of heat or "glow" may very important for comfort and cosiness [43–45], whereas in other countries, even indoor temperatures are a desirable characteristic.

Many of the studies acknowledge that certain technologies involve particular risks, concerns or constraints [40]. These include for example fuel storage for all kinds of fuels (especially biomass), space requirements in general [26,46], disruption of the property and garden (pipes for ground source heat), and problems in operation and maintenance, which are mentioned especially in connection with pellet boilers [46,47]. However, survey studies might not always reveal all constraints or concerns related to particular technologies, since the items are preselected by the researcher. Services, distribution and even packaging can be important for the perceived level of service delivered by, e.g., wood pellet systems [48]. Additional constraints or concerns raised in other types of studies relate to, for example, permitting problems and time-lags [49]. However, the perceived benefits and risks of particular technologies do not only depend on their physical characteristics in relation to the physical characteristics of the homes, but also on whether the technology in question is innovative in the context where it is studied.

3.3. Diverse drivers depending on innovation diffusion stage

Several studies [26,50–52] build on Rogers' [53] innovation diffusion theory. Indeed, the existing research suggests that drivers for people choosing "innovative" systems are different than for systems that have become conventional. However, the idea of what is an innovative system depends on the country context [25]. Heat pumps are not innovative in Norway or Sweden but are in innovative in Germany, whereas the situation is probably vice versa for solar power (see Fig. 1). People choosing innovative systems are driven by environmental considerations and interests in the technology and its particular benefits [54–57]. They are usually younger, more educated and wealthier than the population at large [58] although this could depend on the purchasing price of the innovative system or specifics of the country context – studies from the UK suggest that pioneering consumers can also be recently retired elderly people with disposable time and income [32].

Costs, convenience, perceived risks and recommendations by peers play a larger role for the mass market [56,59]. Social influences (media, advice, recommendations by installers or friends) appear to be important for the majority of owners [38]. Comfort and convenience are major drivers, in particular for heating systems. For example, Owen et al. [39] have examined the special needs of elderly people which is an aspect that is highlighted in some other studies, as well. Their point of departure is that elderly people are usually not particularly innovative. However, they may benefit greatly from the replacement of boilers and burners with other systems that do not require so much cleaning [38,39]. Hence, their needs may be an important factor in the mainstream market [8].

3.4. Major gaps: focus on single-family homeowners and Western Europe

Considering the existing body of research, it is noteworthy that there is much more research on building users' acceptance of particular renewable energy systems from the UK, the Nordic countries and Germany than from other countries. Another noteworthy factor is that there is more research on single-family home owners than on other types of residential buildings. From research focusing mainly on other energy investments, we know that one of the most important factors influencing energy investments in buildings is the type of building and its tenure [61,62].

In terms of floor area, single-family homes and multifamily homes make up approximately equal shares of the total building stock in the EU-27 [63]. However, the share of single-family vs. multifamily dwellings in different European countries varies greatly, with Ireland having 89% single-family homes and Estonia only 25% (Fig. 2). From this perspective, there is clearly a dearth of research on barriers and drivers to the adoption of building-scale renewable energy systems in multifamily buildings. These buildings entail physical features that influence their suitability for building-applied renewable technologies. A hindering factor is the lower roof space relative to number of residents, compared to single-family homes, which reduces the capacity to produce solar heat and power [64,65]. On the other hand, multifamily buildings are more frequently equipped with central heating, which can facilitate the adoption of more expensive systems like biomass or ground source heat, or the use of solar collectors for space heating [66].

There are also important organizational features. In some countries, multifamily buildings consist predominantly of *rental dwellings* (e.g. Germany, France, Belgium, the Netherlands, the UK). The relatively few studies that encompass both owner-occupied and rental dwellers [18,23,27,31,66] show that owners are much more likely to invest than tenants due to the landlord-tenant dilemma [67,68]. In countries where rental housing is rare (Central and Eastern Europe and South Europe), these buildings are particularly problematic due to low incomes of occupants, and there are legal and practical constraints on adding investment costs to the rent [14]. However, in countries where there is a large and well-established professional rental sector (France, Netherlands, Nordic countries), social housing providers can sometimes be forerunners in sustainable energy investments [14,69,70].

In Central and Eastern Europe, Southern Europe and a few other countries, owner-occupancy (condominium associations) is the predominant form of ownership of multifamily dwellings. For example in Spain 94% and in Romania 96% of multifamily dwellings are owner-occupied [71], and the share of owner-occupancy is also growing in other countries due to the privatization of social housing [72]. The more widespread owner-occupied multifamily dwellings are, the more diverse the socioeconomic background of the inhabitants. The barriers to energy investments in these types of dwellings include organizational, psychological and financial problems that are unique to this dwelling type, such as organizational difficulties of reaching agreement on the need to take measures and on the type of measures to be taken. When this is coupled with high majorities for reaching decisions concerning investments and difficulties in raising collective finance, the barriers to energy investments are severe [71]. However, there is little dedicated research on investments in building-scale renewables investment, while existing research suggests that not only barriers, but also drivers, are different from those in single-family homes [52].

4. Factors in the householders' local context

Some of the studies mentioned in Table 1 suggest that novel solutions, especially heating systems, also have different regional diffusion patterns within a country [37,64], which is a rising topic in the literature [65,73]. There is a vibrant literature on peer effects, i.e., the diffusion of residential-scale renewable solutions from one household to another [74,75]. However, the strength of the regional effect seems to suggest a broader 'network effect', which is not only mediated by direct recommendations or imitation, but also through the development of local competences and service markets [76–78]. Several

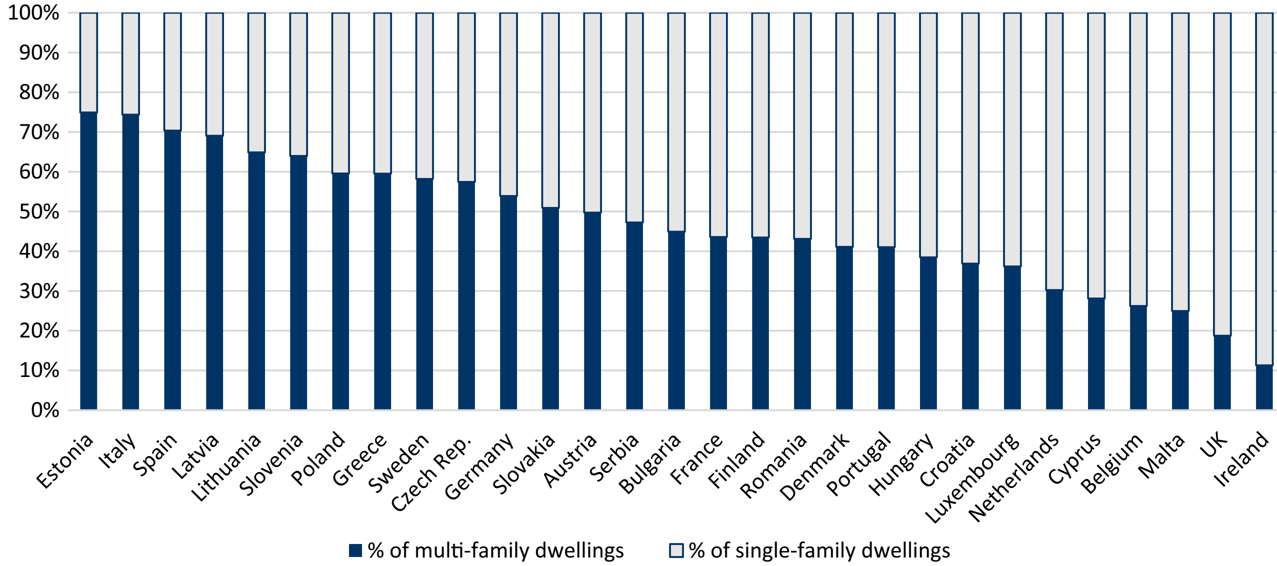

Fig. 2. Share of multi-family and single-family buildings (% of floor area) in the EU-27.
Source: ENTRANZE online database [63].

other factors in the householders' local environment have been found to influence their decisions, such as local promotion programmes and the availability of relevant services.

4.1. Peer effects: the influence of neighbours' behaviour

Many studies stress the importance of social influence, i.e., the influence of recommendations from friends, neighbours or installers on households' decisions [25,52,57,64,76,79]. Indeed, prior adoptions in the neighbourhood (peer effects) have been found in US studies to have an independent effect on the diffusion of new technologies, such as PV panels. Woersdorfer and Kaus [57] examined the propensity of non-adopters to rely on examples and recommendations from friends and neighbours on the decision to adopt solar thermal systems. Müller and Rode [80] found that the propensity to install PV increases with the number of previously installed systems close by in Wiesbaden, Germany and Schaffer and Brun [73] stressed the importance of both peer effects and intermediaries like solar initiatives and installers. Bale et al. [81] analysed the influence of social networks (neighbours, friends, co-workers) in the UK and found significant information exchange concerning both energy renovations and PV installations.

Solar PV panels are highly visible products, which increases the likelihood of social diffusion [53]. Further research would be relevant of whether such effects can be quantified for other building-scale renewable systems such as heat pumps. Even though there is evidence that people learn from each other both passively by observing systems and actively, by exchanging experiences [82], there are also other factors that explain the spatially uneven adoption of building-scale renewable energy systems, namely local organizations and promotion campaigns.

4.2. Local support and promotion campaigns

Several studies have examined the role of various kinds of advice, technical support or funding programmes on householders' energy investments [36,83]. These can be particularly important when building owners are aware of the need to replace building systems but there is significant uncertainty of what are the best solutions for each site, which leads to delays and inertia [18,84]. For example, Jager [66] tested the influence of local information meetings in the Netherlands, and found they strongly decreased the barriers to PV adoption.

Indeed, local organizations, such as solar initiatives [85,86] have been shown to have played an important role in the early diffusion of solar PV in Germany. Schaffer and Brun [73] suggest they continue to do so, especially in municipalities with lower installation levels than the national average. Such organizations have provided information, advice and networking among householders and craftsmen required for the installation process. Mills and Schleich [64] found that households in regions with higher solar thermal adoption levels are more likely to adopt solar (even after controlling for geographic conditions), suggesting information and support at the local or regional level can influence the adoption of solar collectors. Pablo-Romero et al. [87] have investigated the role of national and local policies to promote solar thermal in Spain, including local ordinances, subsidies and tax incentives, including property tax incentives. Gonzales-Limon et al. [88] also show that there is a certain amount of diffusion of progressive policies to neighbouring municipalities.

4.3. Installers and other service providers

Installers are often the main source of information for building owners, and their recommendations have significant weight in the choice of several building systems or components [30,39,89,90]. However, the role of installers does not always appear positively in studies on the replacement of building components or systems. Liu et al. [91] found that poor service level by installers was an important factor causing householders' dissatisfaction with ground source heat pump systems, and Jackson et al. [92] report the same finding for a broader range of building-scale renewable energy systems in the UK. Moreover, Lundh [93] highlighted the installation companies' lack of knowledge and capacity as a major barrier for the diffusion of solar collectors in Sweden and Roy et al. [40] reported difficulties of finding trustworthy installers as a major reason for non-adoption in the UK.

Conversely, Fabrizio and Hawn [94] have shown in the US that solar power installations increased more rapidly (after introduction of an economic incentive for households) in cities where qualified installers were present, i.e., they argue that qualified installers are a critical "complementary good" promoting the diffusion of solar power. Schaffer and Brun [73] report a similar positive influence of qualified installers in Germany.

It is likely that the role of service providers grows when innovative solutions start to enter the mass market. The innovators and early adopters are more likely to make efforts to find new solutions, but latecomers are more likely to rely on solutions that are readily available

[8]. Hence, the knowledge level and awareness of for example engineers or architects, craftsmen, installers, as well as real estate agents, and house managers can influence the acceptability and actual adoption of new solutions. Another factor that is likely to gain importance is quality assurance, monitoring and verification of savings [14]. There is a great deal of discussion on whether technically possible promised savings are realized due to installation, maintenance and use, and due to user behaviour [70,84]. Guarantees and insurance products may also gain importance. Mainstream consumers are not likely to accept even unlikely risks, and the risks of new solutions usually gain much more attention than the risks of old ones [95].

Others service providers can influence investment decisions: Juntunen and Hyysalo [96] describe the potential relevance of various leasing and financing services for the adoption of building-scale renewable energy solutions. Energy companies can have a role in mainstreaming building-scale renewable energy solutions, for example via energy efficiency obligations and by facilitating grid installations. For instance, heating systems (boiler replacement) and other renewable energy technologies are offered in the energy efficiency obligation schemes of several countries [97]. Palm [78] has recently highlighted the important role of local energy companies in promoting and facilitating the local uptake of PV panels in Sweden. Energy companies have also played an important role in the diffusion of heat pumps in Germany and France [21,98] and more recently in Denmark [99]. Moreover, banks are an important source of finance even for conventional improvements such as heating system replacements [100]. In some European countries, banks offer dedicated credit lines for households' renewable energy investments [101].

5. The influence of country context

As shown in the introduction, building-scale renewable energy solutions display widely divergent diffusion patterns across Europe. While some of the household and local contextual factors may serve to explain part of these differences, they are clearly insufficient without a review of country level factors. Some of the most typically recognized drivers and barriers derive from geography, market structure and existing or necessary infrastructure. Policies either enable or inhibit the adoption of renewable energy solutions in buildings. However, research has identified differences in the legitimacy of renewable energy technologies among European countries, which can depend on expert and professional communities, citizen and social movements as well as the media.

5.1. Geography

Geography is an obvious factor influencing the practical feasibility and related market interest in particular solutions. The European countries have very diverse climate conditions, with different numbers of heating and cooling days and different levels of insolation, resulting in different financial returns for building-scale renewable energy investments [11,14,21]. Countries also have different endowments of natural resources like wood, hydroelectricity and various kinds of wastes like sawdust for pellet production, which are likely to influence the relative prices of energy sources, the existence of domestic industrial competencies, and the amount of development effort devoted to related solutions [102]. However, the objective availability of energy sources does not completely explain the amount of (e.g. policy or industry) effort devoted to certain solutions, as evidenced by the uneven historical development of for example solar power [11,103], solar thermal systems [20], pellet heating systems [11] and ground-source heat pumps [21] in Europe.

5.2. Policy

Policy is clearly a driver for the adoption of particular solutions. The most commonly mentioned policy instruments in household surveys are subsidies [27,34,60]. Cansino et al. [104] have presented a comprehensive review of subsidies, tax incentives and other measures offered in the EU-27 for household adoption of solar thermal, geothermal and biomass systems. While such policy measures can have important roles at a certain stage of market development, observations concerning technologies that are cost-competitive at market prices (and for which subsidies have been phased out in many countries) appear to suggest that cost-competitiveness is not a sufficient condition for renewable energy solutions to reach maximum diffusion [105]. This is not surprising given the history of energy efficient solutions, many of which have been cost-efficient for years, yet are still not adopted in households [106].

The dominant focus on financial incentives tends to obscure the role of less observable policy measures applied at early stages of market development. Demonstrations can be important both at early stages of the market, or when a technology attempts to take over a new market segment (e.g., building-integrated PV for larger buildings) [70]. Dewald and Truffer [85] and Strupeit and Neij [86] have shown how important the other measures, such as training, qualification and certification of installers, and overall competence development in society had for the early diffusion of PV in Germany. Similar observations have been made concerning pellet boilers [107] and heat pumps [21]. Technologies that are mature can also be mandated in building codes [12], as has been the case with the solar thermal obligations in several countries in Europe and beyond [101,104]. Indeed, the RES directive [7] requires EU member states to integrate requirements for renewable energy production in building codes.

From this perspective, understanding differences between adoption patterns in European countries might need to take into account not only the current policy intensity, but also the number of years for which supportive policies have been in place. For example, West European countries have a long legacy of policies supporting energy efficiency and renewable energy since the first oil crisis in 1973 [106]. In contrast, the countries that were closely linked to the former Soviet Union did not suffer from a similar fuel shortage [108]. Hence, policies to promote energy efficiency and renewable energy are more institutionalized and have a longer history in the west. A further important aspect of policies to promote renewable energy systems are their consistency, which may depend politically on the presence of co-benefits such as job creation [8].

5.3. Markets, institutions, infrastructures and competing solutions

Markets and companies are naturally important drivers of new solutions, since solutions cannot be adopted unless they are readily available in the market. Most of the solutions discussed above are indeed in principle available throughout Europe, yet there are variations in their accessibility and practical feasibility. This is less critical and variable for components like solar panels, but there can be significant differences in the cost and quality of design, planning and installation services from one country to another [21,45,109].

Markets for building-scale renewable energy systems develop in relation to competing and complementary building and energy systems [110]. As concerns pellets and groundsource heat pumps, the literature suggests that their markets depend on the absence of significant competition in the form of accessible and cheap gas or district heating [98,111–115]. The gas distribution network is well-established in Western Europe [116] and the district heat distribution network in Northern, Central and Eastern Europe [117]. Indeed, households that are not served by gas or district heating networks have been identified as the most promising segments [33,111].

However, the literature also suggests a certain level of competition among the new technologies themselves: heat pumps and pellet boilers are clearly competitors [29,36,38]. If one of these systems manages to occupy the most promising segment, it might crowd out the best opportunities for the other. Solar thermal systems can be competitors or complements to heating systems, depending on the climate and heat demand. Solar thermal systems and solar panels, on the other hand, might have to compete with one another when roof space is scarce.

Other relevant existing infrastructures relate to the age, size, structure and current condition of the building stock, and to the availability of central heating. Building-related institutions can also influence how buildings and their renovations are typically governed and managed (e.g. traditions of co-ownership, traditions of self-renovation) [14]. The capacity of households to make investments also varies considerably across the EU-28, firstly because of purchasing power, which varies across EU-28 countries by more than a factor of 2 [118]. Secondly, access to capital can be a separate, critical factor, since homeowners in several countries are heavily indebted [14]. For example, the high savings rate of German households has been proposed as one reason why the household-driven business model for solar PV has been so successful in Germany [119].

However, problems with existing technologies (such as sharp rises in fuel prices) can also offer opportunities for new solutions [33]. From this perspective, a relevant market factor is the price of electricity and gas for households, which according to Eurostat [98] varies across the EU-28 by a factor of 2 for gas and 3 for electricity.

5.4. Legitimacy of specific technologies

The literature suggests that there are differences in the legitimacy of building-scale renewable energy technologies in different countries [24,120,121], i.e., the extent to which they are recognized as reliable solutions and accepted as economically and socially appropriate ones [122]. Such differences can derive from historical traditions or be influenced by changing market conditions, but they can also be directly influenced by the presence of popular social movements promoting certain technologies, and mediated by the views of experts and professional communities and the mass media (popular press, TV and social media).

Expectations toward energy provision and use in buildings vary both historically and across cultures, even within Europe [123], as is shown, for example, in the variability of thermal comfort expectations in different countries [124]. These differences are due to historical experiences, building traditions and building usage practices [125]. There are also diverse historical experiences of particular solutions. These can be positive and self-reinforcing, such as the recent history of bioenergy in Austria [126] or negative, such as poor historical experiences of early heat pumps [127] or solar thermal installations [128] in the pioneering countries.

Social movements have been shown to play an important role in the early stage of diffusion. Examples include the role of citizen movements for solar water heaters in Austria [76] and Barcelona, Spain [129], and in the early deployment of solar PV [85,130]. Such movements create legitimacy for the new solutions before and while they are promoted by public policy.

Expert and professional communities, such as universities, consultants and professional associations have an important role in introducing and legitimating new technologies [17,131,132]. However, these same expert groups may also be major reproducers of old ideas, which maintain the existing structures [133]. According to Nösperger et al. [134], today's system of building professionals fails to address low-carbon solutions in buildings, since they do not fall within the domain of any existing profession. Hence, a lack of consensus on what are the best solutions for residential buildings can be a factor obstructing public acceptance and creating uncertainty and confusion among the general public [84], as can the need to integrate innovations into existing building structures and fragmented construction supply chains [135]. Such issues like the longstanding existence of voluntary but widely accepted standards or certification schemes might serve as one possible indicator of the level of consensus on appropriate solutions in a country [45,113].

The role of the media has not been examined in many studies yet. However, the media can be important in promoting awareness, but they can also fuel controversies as has been shown concerning the public image of solar power in the Spanish daily press [136]. The media can also maintain outdated views, such as limited understanding of sustainable energy in the Italian press [137]. Since there is very limited research in this area from Europe, and media coverage can be either positive or negative or both [138,139], more research is called for on both the amount and type of media coverage of building-scale renewable energy technologies.

6. Summary and conclusions

6.1. Summary and research gaps

This review has aimed to investigate the literature for answers to the questions: (1) Can research on household adoption criteria for building-scale renewable energy systems be generalized from one European country to another and (2) What propositions can be found in the literature to explain the uneven uptake of building-scale renewable energy solutions in Europe?

As concerns the first research question, our review of the literature concludes that there are a few similarities, but also significant differences in findings across technologies and European countries. Similarities can be found in that some of the household-level drivers and barriers pertain to energy investments in general, and these appear to be robust across countries and across technologies: access to capital and home ownership are significant factors explaining investment in building-scale renewable energy technologies. Educational level and specialization might also belong in this category of factors that promote uptake across countries and technologies, but there are fewer research findings available on them. There are also (though to a less extent, given the smaller number of studies) some findings that emerge as major similarities across countries for a particular technology. Issues like required space and security of supply, for example, appear to be important for pellet boilers across countries. However, in terms of socio-demographic features of adopters and the relevance of environmental motivations, for example, the picture is very mixed.

There are also significantly fewer studies from certain countries, even parts of Europe, than from others. There is a dearth of research from Central and Eastern Europe, which might represent a significantly different market due to differences in the building stock, energy policy traditions, average per capita purchasing power and the current energy market [14]. But since the literature also suggests that drivers, barriers and characteristics of adopters are different at different stages of the diffusion process, it is also unlikely that findings from Northern, Southern or Western Europe can be readily transferred among those countries, either.

As concerns the second research question, i.e., what might explain the uneven uptake of building-scale renewable energy systems in Europe, the literature provides three types of hints for further research on this question.

1. On the household level, three main findings emerge. *First,* home ownership, income (access to capital), education and, to some extent, age have been found to influence householders' propensity to invest in building-scale renewable energy solutions. However, the costs and benefits of solutions (including non-monetary costs and benefits such as comfort and disruption, which can depend on the physical context and cultural expectations of the households), and the real and perceived risks and uncertainties of new technologies play a crucial role. *Second*, it appears to be established that these factors play different roles at different stages of the diffusion process, so that educated, pioneering people with less concern for costs or concrete benefits are critical at the early stage, whereas the mainstream market (often middle-aged, middle-income people) make

adoption decisions based on costs and benefits. *Third*, a factor that has received less attention is the type of physical building stock (share of single-family homes) and the nature of tenure (share of owner-occupancy). It is likely that building-scale renewable energy technologies are diffused more rapidly in countries with a sufficient population of economically comfortable, relatively well-educated single-family homeowners.

2. The local environment appears to play an important but less recognized role at both early stages of diffusion and later, in mature markets. At the early stage, innovative building-scale renewable energy solutions diffuse through active local initiatives and organizations, and via peer effects. At later stages, diffusion is facilitated by the local presence of relevant complementary services (e.g. qualified installers, financial services), which can generate significant network effects, making a particular technology more convenient and accessible than another one.
3. The national context appears to influence which technologies are diffused and how they compete or complement each other through at least the following factors. Geography is an obvious factor, but there is abundant evidence showing that it does not completely explain uneven diffusion patterns. Policy is important, but the literature suggests that besides current policy intensity, also long-term investments in the creation of markets and competencies are likely to make a difference. Several different kinds of markets, for competing and complementary solutions and energy sources, are also likely to play a role in adoption patterns. Indeed, some of the variation in adoption patterns might be explained by competition among building-scale renewable energy solutions themselves for a limited segment of promising customers. Finally, the literature suggests that there are differences in the legitimacy of different solutions in various European countries, due to their 'fit' with local cultures and infrastructures, and the way in which they have been promoted or obstructed by experts, social movements and the media.

6.2. Hypotheses for further research

While there are significant research gaps and a great need for further research to understand the entire European market, the present review of research on adoption at the household, local and country level suggests some promising avenues for further research. The present review has identified factors that could be used to attempt to quantitatively model and explain the diffusion of the four technologies examined here separately, as well as to examine whether common explanatory factors are significant for all technologies (Table 2, which also suggests potential data sources identified in the present review, where available). It would also be interesting to model the importance of these factors separately at different stages of the diffusion process, and taking into account potential competition among building-scale renewable energy systems (e.g., heat pumps vs. pellet boilers).

However, the relevance of the local context, which we highlighted in the present article, does not appear equally amenable to quantitative analysis. The present state of knowledge suggests that more qualitative and case-study research is merited to understand the significance of local level factors in early and later diffusion stages, and their relationships with factors influencing adoption at the household and national levels. The reviewed literature suggests that this is a promising avenue, since it helps to capture such phenomena as changing adoption criteria as we move from early to mainstream markets, the role of peer effects, and indeed the different impact of policy measures as markets mature [8,24,145]. However, the fact that local effects include a broad range of factors suggests that simple 'contagion' models are insufficient, and that there are feedback loops among local demand and local supply of services as markets develop [85].

It is easy to see that country-level policy measures can influence households' decisions and the local provision of complementary services. However, influences might also flow from the local level to the national level [110]. Dewald and Truffer [85] have shown how local solar initiatives were very influential in the development of national-scale policies and support measures for solar PV in Germany. Späth and Rohracher [126] have shown a similar process, from local to national, for bioenergy adoption and legitimation in Austria, and Ornetzeder and Rohracher [146] highlighted the importance of social self-building movements for the later national success of solar collectors in Austria. Gonzales-Limon et al. [147] have shown that local policies may also diffuse to neighbouring municipalities in Spain. These observations suggest the hypothesis that understanding the diffusion of building-scale renewable energy systems is likely to require process analyses that examine how the interrelations between household-level, local and national (or even pan-national) factors at certain opportune times create the conditions for successful diffusion.

Table 2
Factors expected to explain the diffusion level of building-scale renewable energy technologies in the countries of EU-28.

Factors explaining adoption patterns	Potential data sources
Household and building data	
Share of owner-occupied single-family homes %	ENTRANZE database[63]
Household access to capital: savings rat% and average mortgage interest rat%	Eurostat
Median income, PPS	Eurostat
Share of low-income owner-occupants	not available for EU-28, but high share of owner-occupancy (> 90%) and high share of low-income (> 30%) implies a proportion of these are low-income[14]
Educational attainment level of the population, % of population with secondary/tertiary education aged 30–65	Eurostat
Awareness of renewable energy sources	Eurobarometer studies, e.g.[140,141]
Local support infrastructure	
Presence of local organizations promoting the technology	ManagEnergy.net
Availability of qualified suppliers and installers	EHPA EUCERT database[142], EurObserver RES barometers[143]
Availability of other relevant services (utilities, banks offering services for technology acquisition)	Not available Europe-wide
Country level data	
Geographical conditions: heating/cooling degree days, level of insolation	EEA[144], Eurostat
Policy intensity, consistency and duration: number of policy measures in place, consecutive years of policy in place	Odyssee/Mure[145], National Renewable Energy Action Plans, may require dedicated review
Legitimacy: Number of media articles positive/negative, consensus among experts, social movements	Not available, but citizen awareness of renewable energy sources captures some legitimacy issues
For heating systems (bioenergy, heat pumps, solar thermal): cost of most common heating sources in country (gas, district heat, electricity)/kWh, share of households served by gas/ district heat network, %	Eurostat (gas and electricity prices), Euroheat and power (district heat prices), gas connections from Eurogas[116], district heat can be estimated from Dalenbäck and Werner[117]

6.3. Conclusions and implications

This review has shown that there is a growing body of knowledge on household-level factors influencing the adoption of building-scale renewable energy solutions, i.e., solar thermal systems, solar PV, advanced biomass heating systems and heat pumps. However, given the diversity of local and national contexts, studies from one country or concerning one of these technologies cannot be readily generalized to others, even within Europe. Because of this, there are still significant gaps in the necessary knowledge to understand the diffusion of building-scale renewable energy systems across Europe, or to explain why it has proceeded unevenly. The present study has identified where data exist and are lacking, and has proposed hypotheses and measures for further research on the subject. Such research is important for policy makers and for companies and industry associations aiming to increase the market of sustainable energy solutions.

In spite of the existing research gaps, the present review suggests some tentative policy and marketing implications. Both issues of supply and demand have been found to be of importance, which suggests that policy measures are most effective when they are applied simultaneously to increase demand and to support the supply of solutions, in the spirit of "market transformation" [8,135]. Given the fact that buildings are bound by their location, it is likely that such markets are partly local. Another implication is that solutions need to be adapted to the diverse conditions of residential buildings and their owners in Europe in order to promote widespread diffusion (and potentially, to avoid competition among building-scale renewable energy systems). Hence, when diffusion is sought beyond the obvious promising market segment of middle-class owner-occupied single-family homes, new solutions may need to be found for the financing and organization of investments in, for example, owner-occupied and rented multifamily buildings as well as low-income households.

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